PHYSICAL GEOGRAPHY NOTES

TOPICS

1. Hydrology and fluvial processes [pages 1 to 36]
2. Geomorphology [pages 37-64]

ADVANCED LEVEL GEOGRAPHY NOTES

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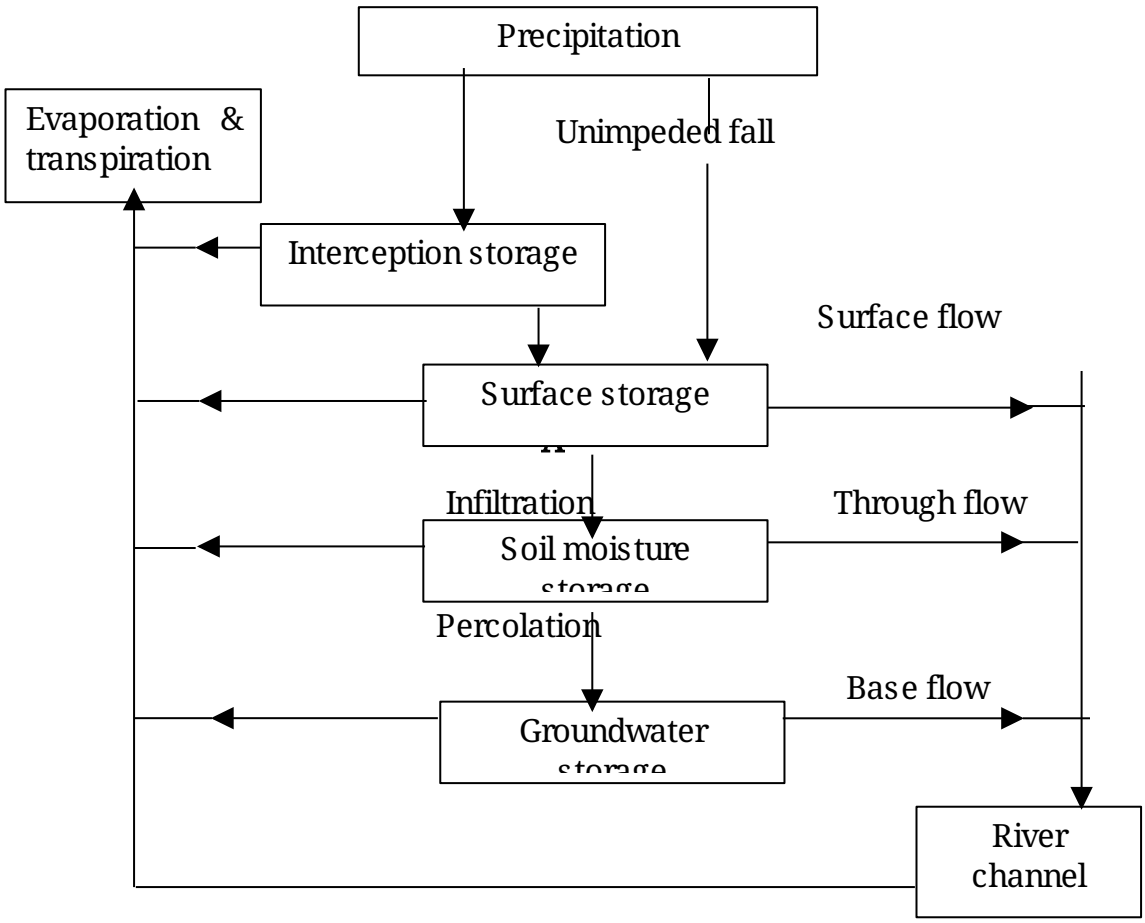
HYDROLOGY AND FLUVIAL PROCESSES

Hydro - means water, while ***logy*** - means study of.

Hydrology - *is therefore the scientific study of water, its occurrence, distribution, movement and storage in the air, on the ground and underground. In short hydrology is a science that is concerned with the study of water.*

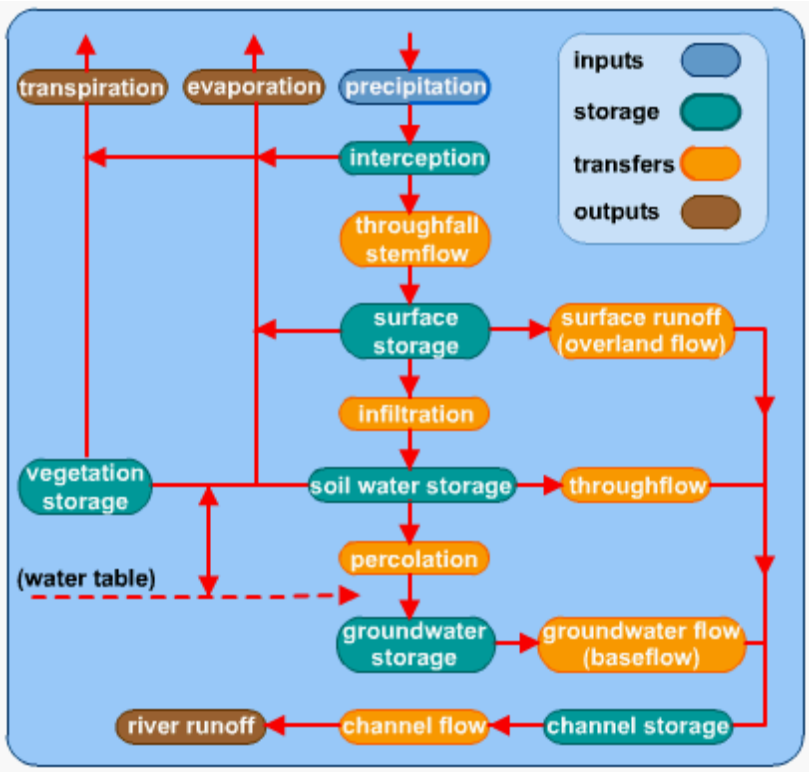
THE GLOBAL HYDROLOGICAL CYCLE (WATER CYCLE)

Refers to the endless interchange of water between the sea, atmosphere and land, or the indefinite circulation of water between the ground, sea and atmosphere. It is made up of a network of storages, transfers as well as transformations (change) of moisture between land, sea and air.



DEFINITIONS

Evapotranspiration- the process of transferring moisture from the earth to the atmosphere by evaporation of water and transpiration from plants or evapotranspiration is the sum of evaporation and transpiration. ET is also defined as the return of water vapour to the atmosphere by evaporation from land and water surfaces and by the transpiration of vegetation.



Evaporation- is a physical process by which water transforms from liquid to gas (atmospheric water vapour) and it occurs on freely exposed surfaces like all surface water bodies and the soil.

Transpiration- is a biological process by which water evaporates from the surface of the leaves through openings called *stomata.*

NB- Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and waterbodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapour through stomata in its leaves.

Precipitation- refers to all forms of moisture (liquid, gas, solid) falling from the sky to the ground e.g. rainfall, snow, hail, sleet, fog and mist. It is an input of the closed hydrological system.

Interception- is a process on which precipitation is prevented from directly hitting the ground by vegetation (tree leaves and branches, including grass and shrubs). Interception also involves a segment of precipitation that is prevented from directly hitting the ground by forest litter lying on forest floors.

Stem flow- is when intercepted water flows down the branches and stems of trees.

Interception loss – is when intercepted water never reaches the ground because it evaporates back into the atmosphere.

Through fall- is when rainwater penetrates through the gaps of the vegetation canopy and falls directly to the ground surface, or simply water that falls directly to the ground undisturbed by vegetation.

Infiltration- is the sinking of water into the ground through the pore spaces available in the soil, under the pull of gravity. Infiltration is responsible for recharging ground water storages. It is also described as the initial entrance of water into the ground, i.e. from the surface subsystem to the soil moisture zone, through soil openings or pores.

Percolation- is the further downward movement of infiltrated water from the soil moisture zone through the zone of aeration and towards the water table (zone of permanent saturation) under the pull of gravity. It recharges ground water storages.

Baseflow- is the lateral or horizontal movement of ground water from one ground water storage to the other, including the effluent of ground water into surface streams. Baseflow is very slow and is responsible for recharging perennial streams.

Overlandflow or surface runoff- is the horizontal movement of water on the ground under the pull of gravity. It occurs either in in unconcentrated forms (overland flow) or following defined channels (channel flow). It is responsible for recharging surface water storages.

NB- overlandflow occurs when precipitation rate exceeds infiltration capacity.

Through flow- is the lateral movement of water just below the surface in a downslope direction under the pull of gravity. It occurs when infiltrated water encounters an impermeable rock surface that would prohibit percolation but instead force water to flow laterally. On reaching the valley sides through flow emerges on the surface to form springs.

Ground water- is the term used to describe all the water found beneath the ground surface (underground water storage).

Surface storage- refers to water that is temporarily or permanently stored on the ground surface after precipitation or snow melting. Temporary storages include water that accumulates in small depressions, small streams, rivers and small dams. Permanent storages on the other hand include large dams, lakes, perennial rivers, seas and oceans.

Permeability- refers to the ability of rocks to transmit water/ allowance of water passage or entrance. Rocks that allow water to pass through e.g. chalk are said to be permeable while those that does not are said to be impermeable.

EVAPOTRANSPIRATION

Refers to a combined process of evaporation and transpiration. Evapotranspiration can be described as actual ET or potential ET

Actual evapotranspiration- refers to the exact amount of water vapour present in the atmosphere that is lost through evaporation and transpiration at any given condition.

Potential ET- is the maximum amount of water vapour that can be added to the atmosphere under given conditions. Or the maximum rate of ET achievable under

certain climatic conditions when the soil is at field capacity.

Field capacity- is when water is continuously available within the soil system.

NB actual ET is always lower than potential ET rates. In deserts there are very high rates of potential ET because the amount of moisture that could be lost is always greater than available moisture, and this leads to a deficit.

Atmospheric factors affecting evapotranspiration

The amount of water that plants transpire varies greatly geographically and over time. There are a number of factors that determine evapotranspiration rates:

Temperature: *Transpiration rates go up as the temperature goes up, especially during the growing season, when the air is warmer due to stronger sunlight and warmer air masses. Higher temperatures cause the plant cells which control the openings (stoma) where water is released to the atmosphere to open, whereas colder temperatures cause the openings to close.*

Relative humidity: *As the relative humidity of the air surrounding the plant rises the transpiration rate falls. It is easier for water to evaporate into dryer air than into more saturated air.*

Wind and air movement: *Increased movement of the air around a plant will result in a higher transpiration rate. This is somewhat related to the relative humidity of the air, in that as water transpires from a leaf, the water saturates the air surrounding the leaf. If there is no wind, the air around the leaf may not move very much, raising the humidity of the air around the leaf. Wind will move the air around, with the result that the more saturated air close to the leaf is replaced by drier air.*

Soil-moisture availability: *When moisture is lacking, plants can begin to senesce (premature ageing, which can result in leaf loss) and transpire less water.*

Type of plant: *Plants transpire water at different rates. Some plants which grow in arid regions, such as cacti and succulents, conserve precious water by transpiring less water than other plants.*

Depth of the water table*: if the water table is closer to the surface, the rate of water uptake by plants is higher and this increase ET rates and vice versa*

INTERCEPTION

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Types of Interception

Primary interception- refers to the first stage of interception whereby raindrops are blocked by tree canopies or grass for the first time. This constitute the biggest part of interception storage.

Secondary interception- refers to the second phase of interception whereby water falling from primary interception is recaptured by foliage beneath the main canopy e.g. grass, small shrubs e.t.c.

FACTORS AFFECTING INTERCEPTION

Interception varies greatly from place to place (spatial variation) and from time to time (temporary variation).

Type of vegetation- there is more interception in the tropical rainforest due to the presence of dense vegetation cover. With a decrease in vegetative cover, the amount of interception also decreases e.g. in desert environments.

Time of the year- in Savanna climates, variation in vegetation cover according to seasons cause variation in interception. In winter for instance, there is less interception because there will be less vegetation cover. With the beginning of a rainy season, interception still remains low because tress will be leafless (deciduous nature of Savanna trees). However, the summer season experience high rates of interception due to an increase in vegetation cover.

Rainfall duration- more interception occurs at the beginning of the storm and decreases as the storm progresses. This is because as the storm continues, vegetation will become saturated. In short-lived storms, much of the rain is lost through interception.

Rainfall frequent- more frequent rainfall has lower interception because will become saturated such that they will not accommodate more water/rain.

Rainfall intensity- high intensity storms have very low interception rates yet light showers like drizzle increase interception.

Human interference- afforestation, deforestation, damming, mining and industrialisation. These either increase or decrease interception.

INFILTRATION

Infiltration is the sinking of water into the ground under the pull of gravity. It proceeds percolation and it occurs when during and after precipitation.

Infiltration capacity- refers to the maximum rate at which a soil in a given condition will absorb water. It is measured in mm/hour.

Infiltration rate- refers to the speed at which water is absorbed by the soil, measured in mm/hr.

NB for factors affecting infiltration see factors affecting surface runoff.

OVERLAND FLOW OR SURFACE RUNOFF

Surface runoff can be defined as gravitational flow of water on the surface either in concentrated forms (rills, rivulets or gullies) or spreading on a wider area (sheet wash).

Overland flow occurs when infiltration capacity is exceeded by rainfall intensity or when the soil gets saturated (saturation overland flow).

Hortonian Overlandflow: Infiltration Excess

According to Horton runoff occurswhen rainfall intensity exceeds infiltration capacity. His theory was that runoff is the result of overland flow produced when precipitation is in excess of the infiltration capacity of the soil. Infiltration capacity is at its greatest at the start of the rainfall but then decreases rapidly due to the compacting of the soil surface by the raindrops, and the inwashing of fine materials into soil openings.

Horton's theory is more applicable in arid and semi-arid regions where little vegetation cover promote the impact of raindrops on the ground resulting in the generation of flash floods. It is also applicable on steep gradients where gravitational force exceeds infiltration capacity. One major weakness of the theory is that it cannot be applied to the rainforests and Horton also failed to take note of other factors other than rainfall intensity that controls runoff.

Saturation overlandflow (Hewlett and Hibbert: 1967)

This theory suggest that overlandflow occurs when the soil is saturated. This situation is possible on gentle gradients and in well vegetated zones (tropical rainforests) where infiltration is promoted. The presence of an impermeable rock mass close to the surface also enhance the saturation of soil leading to the generation of saturation overlandflow.

One major weakness of the theory is that it is inadequate for arid and sparsely vegetated areas.The Hewlett model is also less applicable than the Hortonian model in areas that have hadunusually long periods between rainfall or where transmission losses are high (University ofthe West Indies 2010).

Factors affecting overlandflow and infiltration

In writing these factors, candidates must balance the answer i.e. write factors increasing infiltration/overlandflow as well as factors that reduce infiltration/overlandflow. These factors can either be physical or anthropogenic. Candidates must also be able to distinguish physical factors from anthropogenic/human factors.

Spatial variation- Candidates must also note variations of infiltration/overlandflow from place to place (spatial variation) e.g. from one climate region to another, from rural to urban areas e.t.c. Here, factors that cause variation on a local scale must be excluded.

Temporary variation- variation from time to time e.g. in Savanna, there is seasonal variations. Other examples include changes in landuse e.g. from rural to urban,

changes in land cover through re-vegetation or devegetation, e.t.c. Here spatial variation must be excluded e.g. variation in climate.

Physical factors

Rainfall intensity- determines the impact of raindrops on the ground surface. High intensity storms close the pore spaces in the soil thus increasing the rate of surface runoff. Light showers like drizzle is mostly absorbed through infiltration reducing surface runoff.

Rainfall duration: short-lived storms are usually absorbed by the ground inorder to recharge the soil. At the beginning of the storm, infiltration will be high because the soil will be dry or thirst. But if the storm is prolonged, the soil will become saturated and this will increase overlandflow.

Rainfall frequent: more frequent storms ensures that the soil is always saturated (antecedent moisture is high). As a result, there is more overlandflow in areas which receive rainfall more often than in areas that experience long dry spells.

Precipitation type: rainfall is more absorbed by the ground and is more likely to flow on the ground surface as compared to other forms of precipitation like snow, hail and sleet. Drizzle increase infiltration and lowers surface runoff.

Soil antecedent moisture: refers to the moisture present in the soil before precipitation. The higher the antecedent moisture, the low the infiltration and the higher the surface runoff. The reverse is true when antecedent moisture is low for example in arid environments.

Slope angle: steep slopes encourage high rates of surface flow because gravitational force is higher on such slopes. In addition, thin soils on steep slopes quickly become saturated and this increase surface runoff at the expense of infiltration. On the other hand, infiltration tend to be high on gentle slopes due to little gravitational force.

Geological permeability of the soil (soil/rock type): Permeability refers to the ability of rocks to transmit water/ allowance of water passage or entrance. Permeable rocks or soils (e.g. sand) have high rates of infiltration than impermeable rocks/soils e.g. clay.

Vegetation cover: a dense vegetation cover have the effect of reducing surface runoff yet increasing infiltration rates. This is because vegetation intercepts rain and reduce the impact of raindrops on the ground surface thus reducing rainfall intensity. Vegetation also opens up the soils increasing the passage of water into the ground. On the contrary, water falling on bare surfaces compact the soil, thus sealing the pore spaces. This increase surface runoff at the expense of infiltration.

Drought- reduce vegetation cover and increase the chances of surface runoff at the expense of infiltration.

Human interference

Humans plays a vital role in the modification of runoff and infiltration rates. Humans either increase or reduce infiltration and overlandflow.

Devegetation: refers to the removal of a protective vegetation cover by humans through deforestation, veld fires and overgrazing. The problem of devegetation in the tropics is becoming worse due to overreliance on wood fuel, extraction of wood for other purposes as well as the widespread expansion of agriculture land due to rapid population growth. Devegetation creates bare surfaces and when water falls on such surfaces, pore spaces will be closed by the impact of raindrops. This increase surface runoff and lowers infiltration.

Re-vegetation: through afforestation, regrassing and reforestation programmes, humans increase vegetation cover. As already noted more vegetation means more infiltration and less runoff.

Urbanisation: increase surface runoff but reduce infiltration through the creation of tarmac roads, concrete pavements and artificial drainage systems. These surfaces zero down infiltration but increase surface runoff. Even surfaces that are not covered by concrete can become so compacted such that there will be more surface runoff.

Cultivation: directly increase infiltration by loosening the soil or increasing porosity of the soil. However, if cultivation is done along the slope, farrows left open can be pathways of water, thus increasing surface runoff. The growth of crops bears the same explanation as re-vegetation. See also strip farming, intercropping e.t.c.

Terracing: reduce water movement on slopes directly by reducing the steepness of the slopes.

Mining: is associated with construction of impermeable surfaces e.g. through road construction and housing, all of which increase surface runoff. Mining also increase devegetation.

Industrialisation: have an indirect effect e.g. the formation of acid rain destroying vegetation, climate change and the intensification of drought. It has to be explained convincingly otherwise marks will not be obtained.

Damming: reduce overlandflow by holding water at one place. This increase infiltration and lowers overlandflow downstream.

GROUNDWATER AND THE WATER TABLE

Groundwater refers to all water that occurs beneath the ground surface i.e. in the zone of permanent saturation and above the water table in pores, joints, fissures bedding planes and fractures.

Groundwater is recharged through infiltration and percolation whenever rain is received or when snow melts during spring time. It is also discharged through

direct evaporation, human extraction and plant usage. Groundwater is also discharged into perennial rivers through Baseflow and springs.

Factors affecting groundwater storage

Climate- wet climates like the equatorial climate have more ground water than drier climates like deserts.

Seasonal variation groundwater in the sub-humid seasonal regions varies according to different seasons. For instance, there will be more ground water during the wet summer season while the dry winter season have less groundwater leading to the wilting of plants.

Drought extended dry spells means that groundwater is not recharged and this significantly lower the water table as vegetation and people continue to utilise groundwater.

Climate change the general increase in global temperatures increase evapotranspiration rates resulting in the significant lowering of ground water. Humans are blamed most when it comes to climate change

Rock type porous rocks or aquifers allow groundwater to be recharged thus raising the water table while impermeable rocks/soils discourage infiltration leading to the lowering of ground water.

Vegetation more vegetation means more infiltration when rainfalls hence more ground water.

Humans- affect groundwater in a number of ways which include

Water abstraction through borehole drilling and wells for irrigation and other uses lowers groundwater.

Artificial recharging e.g. through irrigation raise groundwater levels

Devegetation lowers ground water by discouraging infiltration/soil moisture recharge while re-vegetation has the opposed effect.

Urbanisation discourage groundwater recharge hence lowers groundwater.

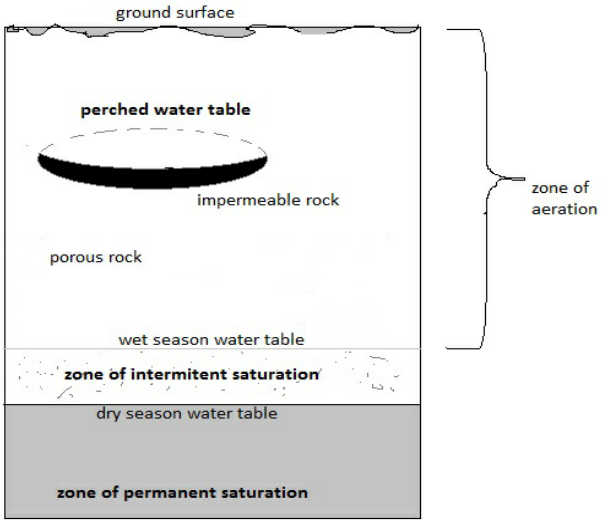
Mining leaves artificial drainage systems, porous mining dumps all of which allow seepage of water thus raising ground water. However, where mining leads to the extraction of groundwater and the creation of impermeable surfaces, groundwater is significantly reduced.

Cultivation loosens the soil, increasing infiltration and groundwater recharge.

Damming raise groundwater by forcing water to stay at one position. Actually damming raise the water table to the surface, thus creating a zone with more ground water around the dams.

WATER TABLE

Water table refers to the uppermost surface of groundwater below which soil is saturated with water that fills all voids and interstices. In other words the water table is the highest level of underground water that separates the zone of permanent saturation from the zone of aeration (non-saturated zone).



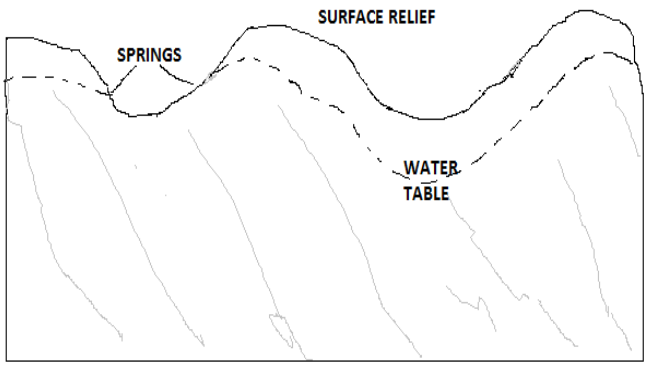
Perched water tables- a perched water table (or perched aquifer) is an aquifer that occurs above the main water table, in the zone of aeration. This occurs when there is an impermeable layer of rock or sediment (aquiclude) or relatively impermeable layer above the main water table/ aquifer but below the surface of the land.

In other words a perched water table is an accumulation of groundwater located above a water table in an unsaturated zone. The groundwater is usually trapped above a soil layer that is impermeable and forms a lens of saturated material in the unsaturated zone.

Factors which affect the form and nature of the water table

i) Surface topography

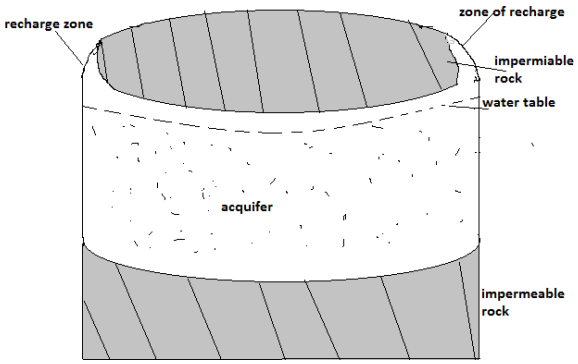
The water table is rarely horizontal, but as R.J Small puts it, the gradient of the water table is in effect a subdued replica of surface relief, which means that it reflects the surface relief. This is because of the influence of capillarity found in soils, sediments and other porous media.



The water table is low in valleys and high on raised land. The slope of the water table is known as the *hydraulic gradient*.

ii) Rock type and geology

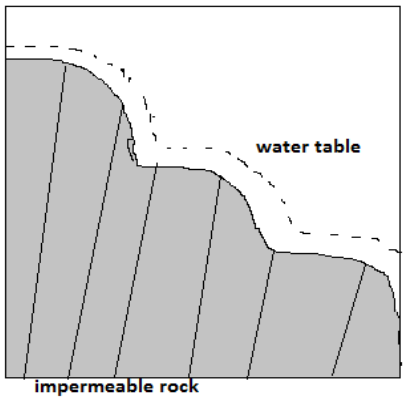
Confined water table- if a permeable rock layer occur between two impermeable layers, a confined water table is formed as shown in the diagram below:



In this case the water does not follow surface gradient but remain confined or sandwiched between two impermeable rock layers. Where an impermeable

rock layer underlain an aquifer an unconfined water table is formed.

Stepped water table- if an area has got impermeable rocks that are synclinal and anticlinal in shape underground, a stepped water table is formed as shown below:



A stepped water table also develops as a result of faulting and the vertical displacement of rock strata. Faulting may actually expose the water table to the ground forming a spring in the process.

Factors waqhich leads to variation in the water table

(i) Seasonal fluctuations in water tables

Water tables varies with seasons especially in sub-humid regions where seasonal variations in rainfall occurs. During the dry winter season, the water table will be low due to absence of rainfall and abstraction of ground water by humans for irrigation. On the other hand, wet summer seasons recharges groundwater thus raising the water table.

(ii) Long-term fluctuations

Include the effect of climate change and droughts on the level of the water table.

(iii) Spatial variations

The water table also varies from place to place e.g. in wet climates, the water table is high /near the surface due to continuous recharge yet in drier climates like deserts the water table is very low due to absence of soil moisture recharge. NB see also human interference described above under section of ground water.

SPRINGS

A **spring** is any natural situation where water flows from an aquifer to the earth's surface. It is a component of the hydrosphere.A spring is a place where water naturally flows out of the ground or a point where the water table intersects with the ground surface such that groundwater will naturally flow out.

Springs are formed from Aquifers. Groundwater is stored in aquifers, which are underground water reservoirs. There are two types of aquifers: confined and unconfined. Confined aquifers are sandwiched between two layers of low permeability soil.

Generally a spring is formed when the pressure in an aquifer causes some of the water to flow out at the surface. This usually happens at low elevations, along hillsides or at the bottom of slopes. Some springs are just tiny trickles of water seeping from the ground, while others are large enough that they create rivers or lakes.

Types of springs

Gravity spring/rock outcrop spring- these form from the pull of gravity. The water gets pulled down through the ground until it reaches a layer it can't penetrate. Because it has nowhere else to go, it starts flowing horizontally until it reaches an opening and water comes out as a spring. These are usually found along *hillsides and cliffs*.

Artesian springs- these come from pressure in confined aquifers forcing the water to the surface. The pressure inside the confined aquifer is less than the pressure outside the aquifer, so the water moves in that direction. Any cracks or holes in the land will easily let the water escape.

Seepage Spring/ valley bottom spring- this is groundwater seeping out of the ground to the surface systems. Seepage springs slowly let water out through loose soil or rock and are often found in land depressions or in valleys.

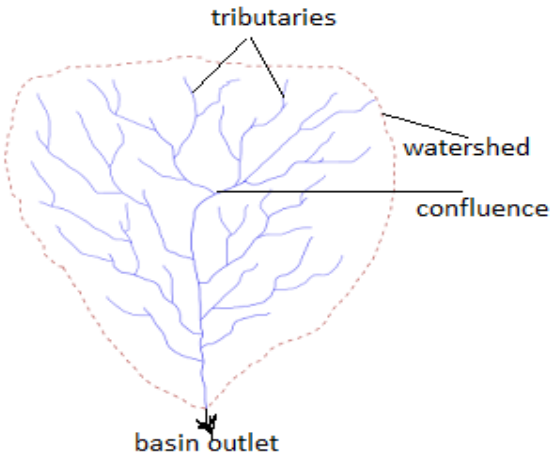
Tubular spring- these springs occur in underground cave systems, which resemble underground highways. These tubes, or channels, are made of limestone rocks which have underground caves that absorb rivers which will re-emerge downstream as a spring. This is the most common type of springs.

Fault/fissure springs- fissure springs occur along large cracks in the ground, like fault lines. They usually develop due to the horizontal displacement of rocks along fault lines, exposing the water table to the surface.

THE DRAINAGE BASIN SYSTEM

Drainage basin- *A drainage basin or catchment area is an area of land drained by a river and its tributaries or an area where surface water from rain, melting snow, or ice converges to a single point at a lower elevation, usually the exit of the basin, where the waters join another water body, such as a river, lake, reservoir, estuary, wetland, sea, or ocean.*

Drainage basins drain into other drainage basins in a hierarchical pattern, with smaller sub-drainage basins combining into larger drainage basins. In closed drainage basins the water converges to a single point inside the basin, known as a sink, which may be a permanent lake, dry lake, or a point where surface water is lost underground. The drainage basin acts as a funnel by collecting all the water within the area covered by the basin and channelling it to a single point.



Each drainage basin is separated topographically from adjacent basins by an elevated perimeter, the ***drainage divide (watershed)*** making up a succession of higher geographical features (such as a ridge, hill or mountains) forming a barrier.

The drainage basin system consists of inputs, flows, storages and outputs.

Inputs- include energy from the sun, precipitation and pressure. Precipitation is the major input of the hydrological drainage basin system.

Flows- include both surface and subsurface movements of water in the form of overlandflow, stream flow, through flow, channel flow, Baseflow, infiltration, percolation, stem flow and leaf drip.

Storages/stores- interception storage, soil moisture storage, surface storage, depressions, ground water storage and all water bodies.

Outputs- evapotranspiration and river discharge (outside the drainage basin)

DRAINAGE DENSITY

Drainage density is the total length of all the streams and rivers in a drainage basin per unit area of the drainage basin usually expressed per km^2. Drainage density is given by the formula:

$$\text{Drainage density} = \frac{\text{length of all streams in the drainage basin}}{\text{total area of the drainage basin}}$$

Drainage density is a measure of how well or how poorly a watershed is drained by stream channels.

Factors affecting drainage density

Drainage density depends upon both climate and physical characteristics of the drainage basin.

Soil permeability (infiltration difficulty) and *underlying rock type* affect the runoff in a watershed; impermeable ground or exposed bedrock will lead to an increase in surface water runoff and therefore to more frequent streams.

Relief or topography- Rugged regions or those with high relief (steep gradients) have a higher drainage density than other drainage basins that are gentler because steep slopes encourage more runoff due to the effect of gravity.

Rainfall intensity- rainfall with high intensity often lead to more surface runoff and high drainage density than rainfall of lower intensity like drizzle.

Landuse- forests versus deforested areas.

Drainage density can affect the shape of a river's hydrograph during a rain storm. Rivers that have a high drainage density will often have a more 'flashy' hydrograph with a steep falling limb. High densities can also indicate a greater flood risk.

Characteristics of high and low-density drainage basins:

High density- *impermeable land surface, steep slopes, limited vegetation cover, limited rainfall, gentle slopes, large channel frequency (tributaries).*

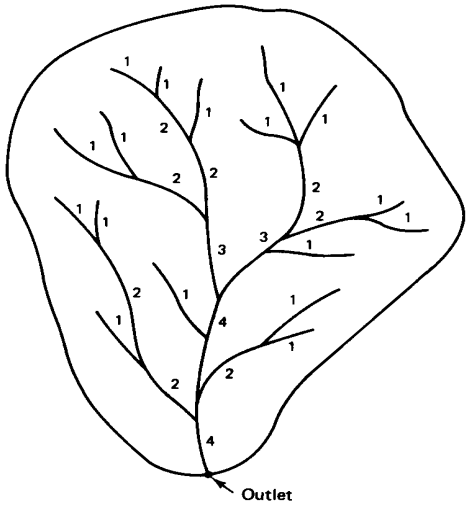
Low density- *Permeable rock, for example, chalk, much vegetation cover, limited rainfall, gentle slopes, lower channel frequency.*

NB- High drainage densities also mean a high *bifurcation ratio.*

STREAM ORDERING

Is another way of quantifying river drainage basin and is used to define stream size based on a hierarchy of tributaries. Horton and Strahler proposed the idea of stream ordering.

In the application of the Strahler stream order to hydrology, each segment of a stream or river within a river network is treated as a node in a tree, with the next segment downstream as its parent.



*When two first-order streams come together, they form a **second-order stream**. When two second-order streams come together, they form a **third-order stream**.* Streams of lower order joining a higher order stream do not change the order of the higher stream. Thus, if a first-order stream joins a second-order stream, it remains a second-order stream. It is not until a second-order stream combines with another second-order stream that it becomes a third-order stream.

BIFURCATION RATIO

Refers to the ratio of the number of stream branches of a given order to the number of stream branches of the next higher order for example the ratio of the number of 1^{st} order streams to that of 2^{nd} order streams. It is given by the formula:

$$\text{bifurcation ratio} = \frac{\text{number of 1st order streams}}{\text{number of 2nd order streams}}$$

Using the diagram above, the bifurcation ratio would be 17 1^{st} order streams divided by 8 2^{nd}order streams thus giving 2.1 as the bifurcation ratio. The bifurcation ratio of an overall hierarchy may be taken by averaging the bifurcation ratios at different orders.

DRAINAGE PATTERNS

Drainage pattern refers to an arrangement of channels that is determined by a number of variables, including soils, geology, structure, present climate, tectonic history and human interferences.

Generic terms used in drainage patterns

- ***Consequent stream****- it is a stream which have its course determined by the original gradient of land surface. Usually it follows the downslope direction.*
- ***Subsequent stream****- it is a stream that joins the consequent stream. Its direction of flow is usually determined by the structure of the rock. Subsequent streams follow lines of weaknesses e.g. fault lines.*
- ***Insequent stream****- is a stream which flows in any direction but for no apparent reason. Such streams demonstrates lack of structural control hence they normally develop in areas of homogeneous rocks forming a dendritic pattern.*
- ***Resequent stream****- it is a stream that flows in the same direction with the consequent stream but at a lower level.*
- ***Obsequent stream****- is the stream that flows in an opposite direction as that of the consequent stream*
- ***Accordant streams****- streams that follow the geological structure and gradient.*
- ***Discordant streams****- streams that cuts across the geological structure e.g. they cut across crystalline mountains and folded regions.*

Factors leading to the initiation of drainage patterns

- Nature of the surface: usually streams follow lines of steepest gradient hence their form is controlled by the nature of the gradient.
- Geological structure: this is the influence of rock type. Streams usually follow regions of weaker rocks and avoid resistant rocks. Streams that follow geological structure are form accordant drainage patterns.
- Faulting- on faulted areas, steams follow fault lines hence the nature of drainage pattern may be influenced by faulting.

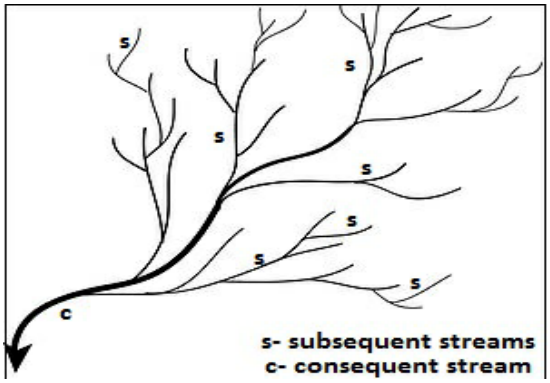
Drainage patterns tend to develop along zones where rock type and structure are most easily eroded. Thus various types of drainage patterns develop in a region and these drainage patterns reflect the structure of the rock.

ACCORDANT DRAINAGE PATTERNS

A drainage system is described as accordant if its pattern correlates to the structure and relief of the landscape over which it flows.

Dendritic drainage pattern

Dendritic drainage patterns are most common. This pattern resemble the vein patterns in leaves. It looks like a tree and its branches. The term dendritic was been taken from the Greek word '*dendron*' meaning a tree. They develop on a land surface where the underlying rock is of uniform resistance to erosion.

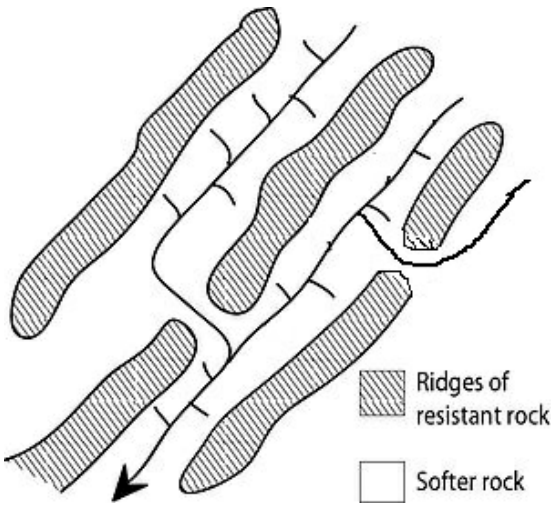


Dendritic drainage pattern is characterized by irregular branching of tributary streams flowing in many directions and at almost any angles, although usually at less than a right angle. Such a pattern develops upon rocks of uniform resistance and demonstrates lack of structural control.

Dendritic drainage pattern also develops on gentle gradients where the velocity of water is lower.

Trellis drainage pattern

The trellis drainage pattern is characteristic of a dipping or folded topography, which exists in nearly parallel mountains, where drainage patterns are controlled by rock structures of variable resistance (rocks with alternate bands of hard and soft rocks).This pattern is found in areas where hard and soft rocks occur in almost parallel bands.



In trellis drainage pattern subsequent streams enter the main river at approximately 90 degree angle, causing a trellis-like appearance of the drainage system. Trellis drainage is characteristic of folded mountains, such as the Appalachian Mountains in North America.

The main streams are directed by the parallel folded structures, whereas smaller streams are at work on adjacent slopes, joining the main stream at right angles.

In this drainage pattern the consequent streams follow the direction of dip and the subsequent streams follow the direction of strike. Obsequent streams are common here and they flow in a counter-dip direction.

Radial drainage pattern:

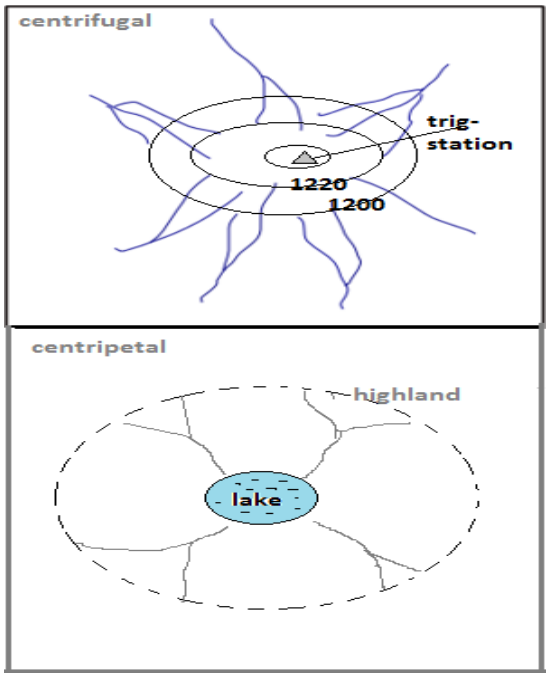
Radial drainage pattern takes ***two*** forms i.e. centrifugal and centripetal.

Centrifugal

A centrifugal drainage pattern results from streams flowing off a central peak or dome, such as a volcanic mountain, (where streams radiate outwards from the central high point).This pattern may also be found on various other types of isolated conical or sub- conical hills.

The radial drainage pattern resembles the spokes of a bicycle wheel. The radial drainage pattern found in Sri Lanka where the streams rising over the Central

Highlands radiate in all directions is a typical example.



The centrifugal drainage pattern is the most common type of radial drainage pattern. Sometimes it is triggered by the intrusion of molten rocks below the surface forming granite rocks.

Centripetal

This is the drainage pattern, as the term 'centripetal' implies, in which the streams drain radically inwards, either towards a single main stream which drains the basin, or to a lake which may or may not have an outlet.

Such patterns are found on sinkholes, craters and other basin-like depressions. This drainage pattern is also called endorheic drainage which refers to an inward flowing pattern of drainage in the world's semi-arid zones.

Annular drainage pattern

In an annular drainage pattern streams follow a roughly circular or concentric path along a belt of weak rock, resembling in plan a ring-like pattern. It is best displayed by streams draining a maturely dissected structural dome or basin where erosion has exposed rimming sedimentary strata of greatly varying degrees of hardness, as in the Red Valley, which nearly encircles the domical structure of the Black Hills of South Dakota. This drainage pattern is an example of structural control. The subsequent streams find it easier to erode the concentric, less resistant strata.

Rectangular drainage pattern

Rectangular patterns occur where streams are guided by intersecting joints, usually in plutonic or metamorphic rocks. It is characterized by right- angled bends and right-angled junctions between tributaries and the principal stream.

It results from the structural control imposed by the jointing or fault pattern of the underlying rocks. It differs from trellis pattern drainage, since it is more irregular and its tributary streams are not as long or as parallel as in trellis drainage.

Deranged drainage pattern

A deranged drainage system is a drainage system in drainage basins where there is no coherent pattern to the rivers and lakes. It represents a drainage pattern which is found in the glaciated shield regions of Canada and Northern Europe with no clear geometry in the drainage and no true river valley pattern. This pattern develops due to the fact that no sufficient time was available for the drainage to become adjusted to the structures of the underlying glacial drift of the recently vacated ice sheets.

The picture presented by the drainage system is very confusing, since there are numerous water courses, lakes and swamps, some interconnected, and some in local drainage basins of their own. In fact, in such glaciated regions the pre-glacial drainage has been completely destroyed and the new drainage could not have time to develop any significant degree of integration.

Parallel drainage pattern

A parallel drainage system is a pattern of rivers caused by steep slopes. Because of the steep slopes, the streams are swift and straight, with very few tributaries, and all flow in the same direction. This system forms on uniformly sloping surfaces.

A parallel pattern also develops in regions of parallel, elongated landforms like outcropping resistant rock bands. Streams tend to stretch out in a parallel-like fashion following the slope of the surface. A parallel pattern sometimes indicates the presence of a major fault that cuts across an area of steeply folded bedrock.

DISCORDANT DRAINAGE PATTERNS

A drainage pattern is described as discordant if it does not correlate to the topology and geology of the area. Discordant drainage patterns are classified into two main types: antecedent and superimposed. In looking at the landscape, it is often evident that streams sometimes cut through deformed terrain seemingly ignoring the geologic structures and hardness of the rock.

Superimposed drainage pattern

If a stream initially develops on younger strata made of soft material and then cuts downward into the underlying deformed strata while maintaining the course developed in the younger strata notwithstanding the newly exposed surface, it is referred to as a superimposed stream.This is because the stream pattern was superimposed on the underlying rocks. In such cases, river directions relate to the former cover of soft rocks that was removed by denudation.

Antecedent pattern

If tectonic uplift raises the ground beneath established streams and if erosion keeps pace with uplift, the stream will cut downward and maintain its original course. In such a case, the stream is called an antecedent stream, because the stream was present before the uplift occurred.

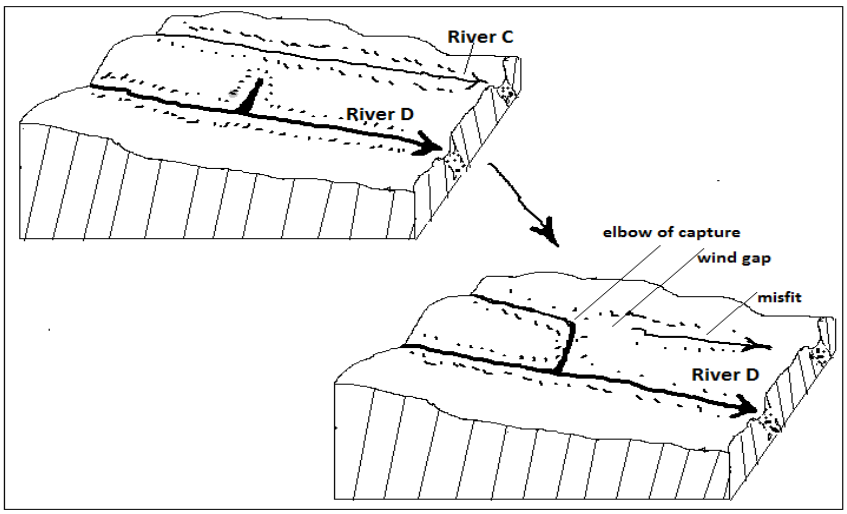
RIVER CAPTURE OR STEAM PIRACY

Stream capture, river capture, or stream piracy is a geomorphological phenomenon occurring when a stream or river drainage system is diverted from its own course, and flows instead down the bed of a neighbouring stream.

In other words river capture is a process whereby the headwaters of another stream are captured by a nearby stream via a subsequent stream. This can happen for several reasons, including:

- Tectonic earth movements, where the slope of the land changes, and the stream is tipped out of its former course
- Natural damming, such as by a landslide or ice sheet

- Erosion, either
- Headward erosion of one stream valley upwards into another, or
- Lateral erosion of a meander through the higher ground dividing the adjacent streams.
- Within an area of karst topography, where streams may sink, or flow underground (a sinking or losing stream) and then reappear in a nearby stream valley



On the diagram, river D is flowing parallel to river C and river D has a substream. The substream on D extends towards C by headward erosion until the headwaters of stream C are captured by D.

Diagnostic features of river piracy

- Existence of an elbow of capture, characterised by a sharp change in the course of the river.
- Presence of a misfit or beheaded stream which can later be a dry channel
- Presence of a wind-gap which is dry ground between the diverted stream and the misfit.
- The migration of the watershed of a subsequent stream.

THE CONCEPT OF THE WATER BALANCE

The water balance/budget refers to the balance or equilibrium between inputs (inflows or gains) and outputs (outflows or losses) in a drainage basin. Inputs include precipitation while outputs include runoff and evapotranspiration. The water balance can be shown using the formula:

$$P = Q + E + \Delta S$$

Where:

P is precipitation

Qis runoff

Eis evapotranspiration

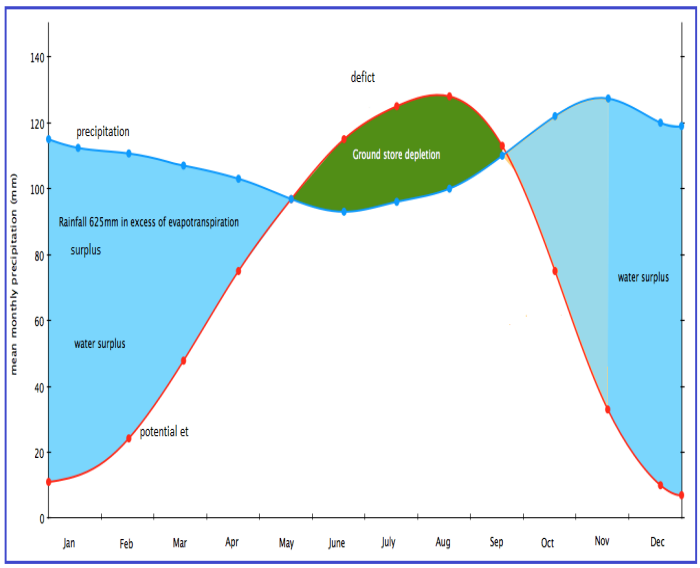
Sis the change in storage (in soil or the bedrock)

This equation uses the principles of conservation of mass in a closed system, whereby any water entering a system (via precipitation), must be transferred into either evaporation, surface runoff (eventually reaching the channel and leaving in the form of river discharge), or stored in the ground.

A water balance can be used to help manage water supply and predict where there may be water shortages. It is also used in irrigation, runoff assessment, flood control and pollution control. Further it is used in the design of subsurface drainage systems which may be horizontal

(i.e. using pipes, tile drains or ditches) or vertical (drainage by wells).

The water balance can be illustrated using a water balance graph which plots levels of precipitation and evapotranspiration often on a monthly scale as shown below:

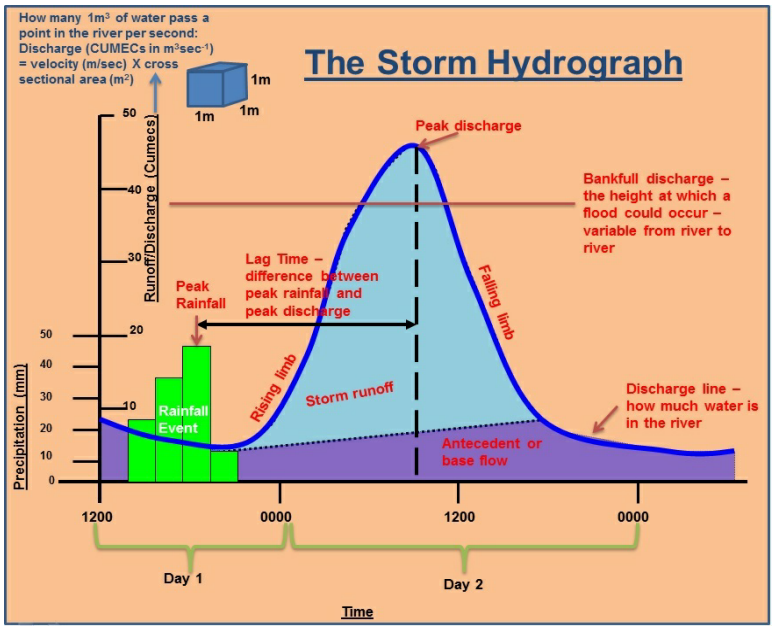


The general water balance in the Savanna (e.g. Zimbabwe) shows seasonal patterns. In wet seasons precipitation is greater than ET which creates a *water surplus*. Ground stores fill with water which results in increased surface runoff, higher discharge and higher river levels. aThis means there is a ***positive water balance***. In drier seasons evapotranspiration exceeds precipitation. As plants absorb water ground stores are depleted. There is a *water deficit* in this season which creates a ***negative water balance***.

NB- water budget is mainly affected by climate. Humid environments have positive water balances throughout the year while deserts have negative water balance most of the time leading to the wilting of plants.

THE STORM HYDROGRAPH

Storm hydrographs are graphs that show how a drainage basin responds to an episode of rainfall. Or a graph which shows variation in river discharge following an episode of rain plotted against time (RJ Small). See diagram below:



THE MAIN FEATURES OF THE STORM HYDROGRAPH

Approach segment- *refers to the river flow before the storm (antecedent flow)*

Rising limb*: The rising limb of hydrograph reflects a prolonged increase in discharge from a catchment area, typically in response to a rainfall event.*

Recession (or falling) limb*: The recession limb extends from the peak flow rate onward. The recession limb represents the withdrawal of water from the storage*

built up in the basin during the earlier phases of the hydrograph.

***Peak rainfall** – the point on a flood hydrograph when rainfall is at its greatest.*

***Lag time**: the time interval from the peak rainfall excess to peak discharge or period of time between the peak rainfall and peak discharge.*

***Discharge**: the rate of flow (volume per unit time) passing a specific location in a river or other channel*

***Peak discharge** – the point on a flood hydrograph when river discharge is at its greatest.*

***Bankfull discharge** – the maximum discharge that a particular river channel is capable of carrying without flooding.*

***Flood** – when the capacity of a river is exceeded and water flows over its banks or beyond bankfull discharge.*

***Base flow** – represents the normal day to day discharge of the river and is the consequence of groundwater seeping into the river channel.*

Physical Factors affecting Storm Hydrographs

There are a range of physical factors that affect the shape of a storm hydrograph. These include:

Size of the drainage basin- Large drainage basins catch more precipitation so have a higher peak discharge and longer lag time compared to smaller basins. Smaller basins generally have shorter lag times because precipitation does not have as far to travel.

Shape of the drainage basin- Drainage basins that are more circular in shape lead to shorter lag time,fairly steep rising limb and a high peak discharge because water has a shorter distance to travel to reach a river (all points in the drainage basin are equidistant from the river so all the precipitation reaches the river at the same time).For a circular drainage basin, the river's hydrograph can often be described as "flashy." Elongated basins are have the opposite.

Relief/topography- Drainage basins with steep slopes tend to have shorter lag times and a flashier hydrograph than basins with gentle gradients. This is because water flows more quickly on the steep slopes down to the river.Basins with steep slopes will have a high peak discharge because the water can travel faster downhill.

Drainage density- Basins that have many streams (high drainage density) drain more quickly so have a shorter lag timeand a fairly steep falling limb.

Antecedent moisture- If the drainage basin is already saturated then surface runoff increases due to the reduction in infiltration. Rainwater enters the river quicker, reducing lag times, as surface runoff is faster than Baseflow or through flow.

Rock/soil type- if the rock type within the river basin is impermeable surface runoff will be higher, through flow and infiltration will also be reduced meaning a reduction

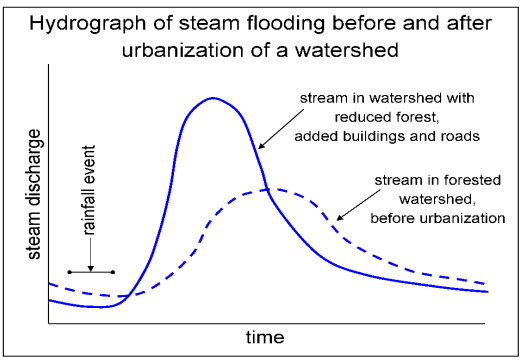
in lag time and an increase in peak discharge.

Vegetation cover- Vegetation intercepts precipitation and slows the movement of water into river channels. This increases lag time. Water is also lost due to evaporation and transpiration from the vegetation. This reduces the peak discharge of a river.Loss of vegetation therefore reduce lag time and increase peak discharge. Rainwater falling on bare surfaces seal the pore spaces thus increasing the amount of discharge.

Amount and type of precipitation- The amount precipitation can have an effect on the storm hydrograph. Heavy storms result in more water entering the drainage basin which results in a higher discharge. The type of precipitation can also have an impact. The lag time is likely to be greater if the precipitation is snow rather than rain. This is because snow takes time to melt before the water enters the river channel. When there is rapid melting of snow the peak discharge could be high. See also rainfall intensity.

Human factors affecting storm hydrographs

Urbanisation- Humans will normally cover soil in impermeable materials like tarmac or concrete which will increase surface run off and reduce the amount of water being stored, increasing the peak discharge and reducing the lag time.


Hydrograph of steam flooding before and after urbanization of a watershed
steam discharge
rainfall event
stream in watershed with reduced forest, added buildings and roads
stream in forested watershed, before urbanization
time

As water doesn't infiltrate easily in urban areas humans often build storm drains that run directly into a river, reducing the lag time and increasing the river's peak discharge.

Artificial drainage systems- Drainage systems that have been created by humans lead to a short lag time and high peak discharge as water cannot evaporate or infiltrate into the soil.

Overgrazing, deforestation and veld fires (devegetation) - these activities by humans create bare surfaces. This increase river discharge and shorten lag time leading to the formation of a flashier hydrograph.

See also cultivation, afforestation and reforestation- these activities actually increase infiltration rates by creating a porous soil environment and intercepting rain. Altogether, these activities reduce discharge and also delay peak discharge (long lag time). However the recession limb of areas with forests, crops and cultivated areas tend to be gentle since water takes time in rivers whose surrounding soil is saturated.

ASPECTS OF A RIVER SYSTEM

RIVER DISCHARGE

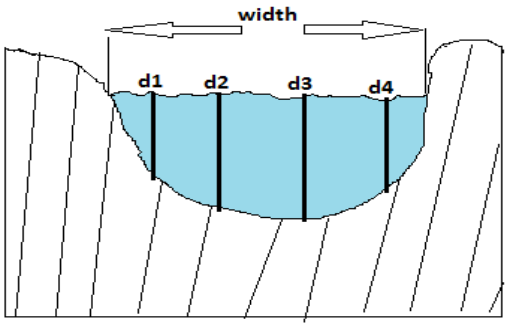
River discharge is defined as the volume of water passing a measuring point or gauging station in a river in a given time. It is measured in cubic metres per second (*cumecs*). Discharge is measured by the formula:

Q =AV

Where **Q** is discharge, **A** is cross-sectional area and **V** is velocity.

How A is determined - the cross-sectional area of a river is obtained by multiplying the width from one bank to the other by the average depth of the river as shown below:

[**A=WxAD** in m^2] where **W** is width and **AD** is average depth



By adding d1, d2, d3, and d4 and dividing by 4, the average depth is obtained. This average depth will be multiplied by the width to get the cross-sectional area. The cross-sectional area will be multiplied by velocity and discharge is obtained.

Human interference with river discharge

Water extraction- the extraction of water for domestic use and for irrigation lowers river discharge especially recharge does not occur. Irrigation and industries utilises large volumes of water and resultantly lower discharge of rivers.

Dam construction- reduce discharge downstream to an extend that small streams could dry up downstream. On the other hand it increase discharge upstream especially for large rivers where dams are constructed.

Urbanisation- the creation of concrete pavements, tarmac roads and artificial drainage systems zero down infiltration and increase the risk of flash floods. However, such impermeable surfaces created in urban areas leave no room for return flow.

Deforestation- increase river discharge due to the absence of interception and reduced infiltration.

Afforestation- has the opposite effect as deforestation.

Global warming- continuous emissions of carbon-containing substances into the atmosphere has resulted in global warming and climate change. This increased the risk of drought lowering river discharge in the process. Rain has become erratic and rivers are drying up as a consequence.

Farming- increase soil porosity and infiltration hence discharge is lowered. However if farming is done on slopes, overland flow is encouraged especially if terracing is not done and this increase the risk of siltation.

General mismanagement of land in communal areas - this cause a lot of soil erosion leading to the siltation of rivers. Siltation reduce river depths thus lowering the water-holding capacity of rivers and as a result, discharge of rivers will be lowered in the long run. Some perennial rivers are becoming intermittent as a result of siltation e.g. the Save River in Zimbabwe.

RIVER VELOCITY

Velocity is the speed of water in the river measured in metres per second. Velocity is determined as follows (float method)

- Mark 2 points along the river and measure the distance
- Place a floating object at point A and observe time taken by the object to reach the second point
- Use the formula V= Distance/time to calculate velocity.
- Record velocity in metres per second

NB- Velocity is also measured using the current meter placed at different points and averaged.

Velocity is mainly influenced by channel shape, wetted perimeter (total area of banks and bed in contact with water), channel roughness or frictional drag and channel slope.

RIVER LOAD

River load is the material which is actually transported and deposited by the river. The competence of a river to transport its load is determined by looking at the largest particles transported by the river.

River regime

River regime is the term used to describe the annual variations in discharge of rivers. There are three types of river regime which are

a) Single regime- where all rivers have one peak discharge per year, typical of rivers in seasonally humid environments. This regime shows one peak Q in summer when rain is received.

b) Double regime- occurs when a drainage basin has w types of inputs, i.e. rainfall and snowmelt e.g. in European countries where 4 distinct seasons are experienced [summer, spring, winter and autumn]. The first peak discharge is experienced due to melting of snow during spring time and the second peak occurs during summer rains. See RhineRiver in Germany.

c) Complex regime- is a regime with several peaks e.g. the Mississippi River. Such rivers have tributaries located in different climatic regions leading to a complex regime.

CHANNEL FLOW

Channel flow is the form of overlandflow whereby water follows defined channels

usually rivers, streams and sub-streams.

Types of flows

- *Laminar flow*- is the horizontal movement of water downstream without disturbing sediments. Laminar flow is rarely found in rivers.
- *Turbulent flow*- consists of a series of erratic eddies formed by water either horizontally or vertically. It is a common type of flow and it is responsible for the disturbance and uplifting of particles. Turbulent flow often increase when velocity increase because water will overcome the frictional drag of the channel.
- *Helicoidal flow*- is a corkscrew movement of water which produces a series of diverging and converging lateral relations. When the water converges, erosion occurs on the outer bank and when it diverges it deposits material on the inner bank. This type of flow is mostly seen on meandering channels.

Rivers are classified according to the nature of their discharge over time as

a) *Ephemeral rivers/streams/channels*- those that flow for a very short period of time following an episode of rain. They are mainly found in deserts following erratic storms that occurs there.

b) *Intermittent rivers/channels*- maintain a seasonal flow of water, hence they flow only during the wet season, becoming dry during the winter season.

c) *Perennial rivers*- these flow throughout the year. They are constantly recharged by Baseflow from the zone of permanent saturation e.g. Limpopo, Zambezi and the Nile river (Nile river is the longest river in the world).

THE LONG PROFILE OF A RIVER

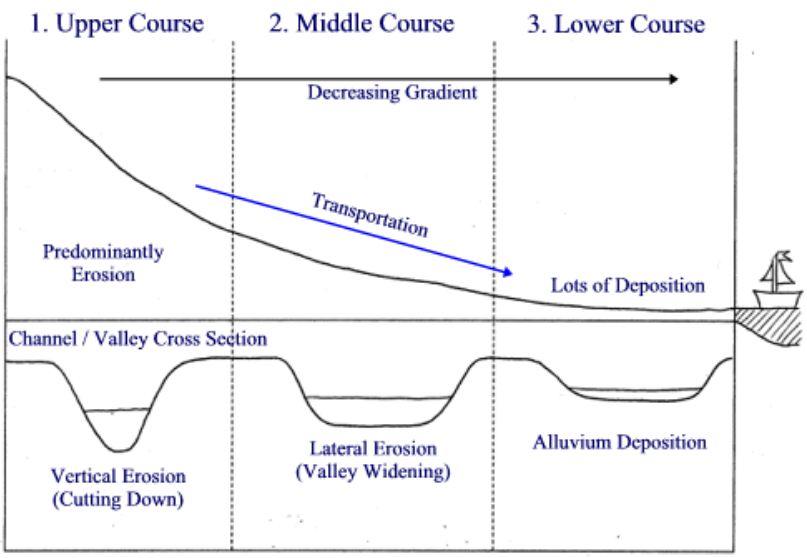
The long profile shows how a river's gradient changes as it flows from its source to its mouth. The course a river takes is split into three stages, the ***upper, middle*** and ***lower*** stages. In the upper course, the river is close to its source and high above its base level (the lowest point the river can erode to). In the lower stage the river is close to the mouth and not far above its base level. In the middle stage, it's somewhere in between.

The total energy that a river possesses varies from one stage to another because of changes in the river's height, gradient and speed. In the upper course, the gradient of the river is steep and the river is high above sea level giving it a large amount of gravitational energy. In the middle course, the river's gravitational energy is lowerbecause the gradient begins to level out. By the time the river reaches its lower stage, it has very little gravitational energy. It is this gravitational energy that

determines the velocity of water and its erosive power, hence the resultant landforms.

Throughout the long profile of a river, deposition and erosion are balanced meaning that, given enough time, the river's long profile would become a smooth, concave, ***graded profile*** and all the knick points would be eliminated as they are either eroded or filled in by deposition. It would take a long time for a river's long profile to become a graded profile though so the idea of a graded profile is, essentially, theoretical as it doesn't really occur in nature.

The long profile of the river is illustrated in the diagram below:



The long profile shows how, in the upper stage of a river's course, the river's gradient is steep but it gradually flattens out as the river erodes towards its base level. One thing to note is the presence of ***knickpoints*** in the long profile. These are points where the gradient of the river changes suddenly and can be caused by landforms like m mwaterfalls or lakes, where the lithology of the river changes and differential erosion takes place. Knickpoints can also be the result of rejuvenation, where the base level of the river falls giving it some extra gravitational potential energy to erode vertically.

Processes in the Upper Course

In the upper course, the river has a lot of erosive power giving rise to great vertical incision. The bed of the river is eroded greatly while the banks arenot eroded much. Vertical erosion is also caused by the traction/dragging of large pieces of angular rock which increases erosion of the bed by corrasion. Vertical erosion is further increased by the rough nature of the channel in the upper course which increases the water's turbulence and its ability to erode. Vertical erosion in the upper course results in the formation of 'V'-shaped channels.

Processes in the Middle Course

In the middle course, the river has less gravitational energy so erosion shifts from vertical to lateral erosion. Since the stream competence is lower in the middle course, deposition of large materials begins here which means that there is a balance between erosion and deposition. Meandering channels are also found here

and the cross-profiles tend to be "U"-shaped due to lateral erosion.

Processes in the Lower Course

In the lower course, the river has next to no gravitational energy so erosion is almost zero. The river's load is mainly composed of silts and clays and it is transported in suspension or even solution. Like in the middle course, when the river floods it deposits its load but deposition now also takes place at the mouth of the river where the river meets the sea or a stationary body of water.

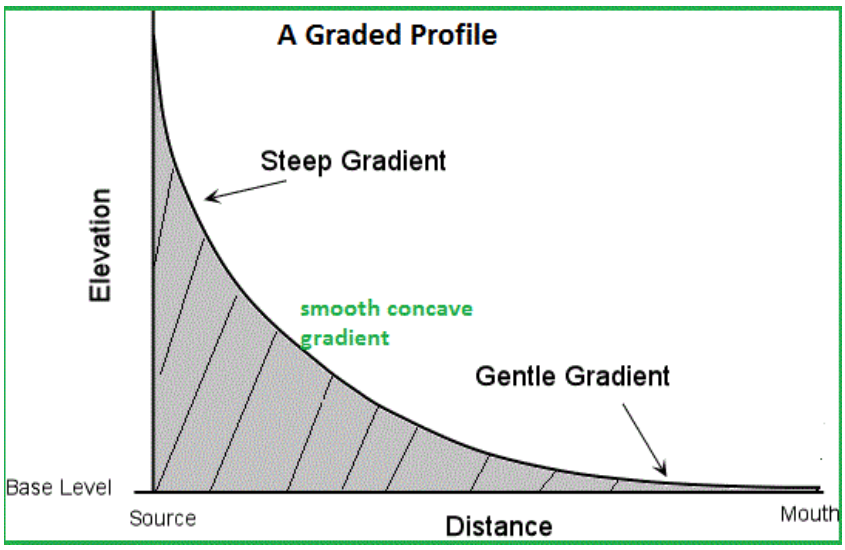
THE CONCEPT OF 'GRADE'

River 'grading' refers to the state of dynamic equilibrium in a river whereby the total energy of a river is sufficient enough to move its load without eroding its channel. In other words the concept of 'grade' is a state of balance between erosion and deposition such that the river is now incapable of eroding but merely transporting its load. It is a theoretical concept difficult to find in most rivers.

NB- fully graded profiles are incapable of eroding their beds vertically but they can erode laterally.

A GRADED RIVER PROFILE

A graded river profile describes a river that has attained a smooth gently sloping concave profile from source to mouth; with the gradient decreasing towards the mouth. All Lakes along the channel would have been filled with sediments and all waterfalls and rapids (knick points) destroyed to form a smooth gently sloping concave profile.

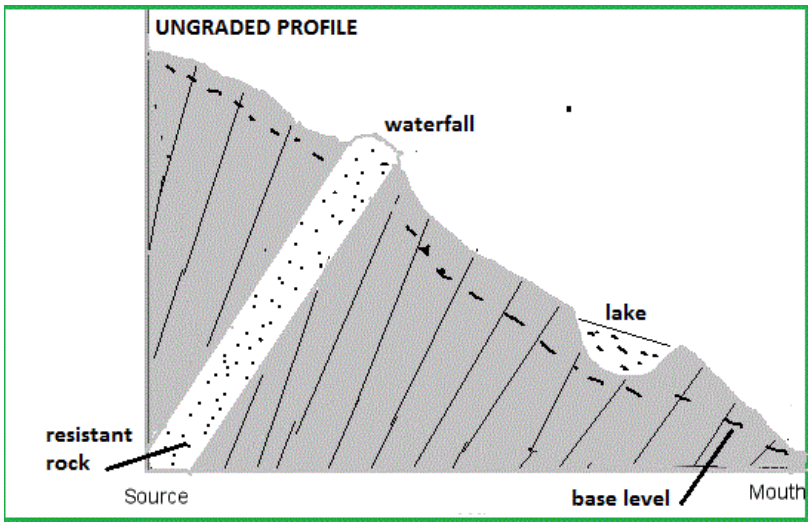


A graded profile is usually a characteristic feature of mature rivers whose base levels hasn't been disturbed for a longer period of time. Examples of rivers with graded profiles include the Rhine River in Germany and the Thanes River in UK. NB the Zambezi River in Zimbabwe is ungraded because it still has a waterfall. As shown on the diagram a graded river profile is the one that has no depressions, Lakes, waterfalls and rapids. It shows a profile of a river in its maturity stage although scholars believe that it is a dynamic state of the river which means it is subject to change any time. Changes that are likely to occur include base level changes (rejuvenation) which gives the river high erosive power. Base

level change actually forms knick points which are characteristic features of an ungraded profile.

UNGRADED RIVER PROFILE

This is a profile that is not yet graded, which still have steep gradients from source to mouth; and punctuated by rapids and waterfalls (knick points) as well as Lakes that still have to be filled with sediments.



An ungraded long profile is thus the one that still has some irregularities from source to mouth. A good example is the Zambezi River which still has waterfalls like Victoria Falls, a lot of rapids and dams e.g. the Kariba Dam, and Cabbora Bassa in Mozambique. Note that a graded profile can change to become ungraded due to changes in base level.

NB- on the waterfall, erosion will exceed deposition until the knick point disappears while on the lake, deposition will exceed erosion until it is filled in with sediments. This will create a graded profile.

REJUVENATION

The term rejuvenation is used to describe the return of an episode of active vertical erosion or youthful stage of a river following an uplift. The base level of the river falls as giving it some extra gravitational potential energy to erode vertically. In short rejuvenation is the return of the youthful stage of the river. Degrading occurs after rejuvenation such that the river's profile would become graded again.

BASE LEVEL

Base level*is the lowest level to which erosion by running water can take place. In the cases of rivers, the theoretical limit of erosion is sea level which means that rivers cannot erode below the level of the sea otherwise sea water will flow back to rivers.*

Base level change*is a process whereby the base level of a river changes. Base level changes occurs as a result of tectonic uplift or as a result of climate change from wet to dry (base level falls) or dry to wet (base level rises). Base level changes can either be positive or negative.*

Positive base level change*- occurs when the sea level rises in relation to land or*

land sinks in relation to the sea. This results in the decrease in gradient of the river and the corresponding deposition of sediments.

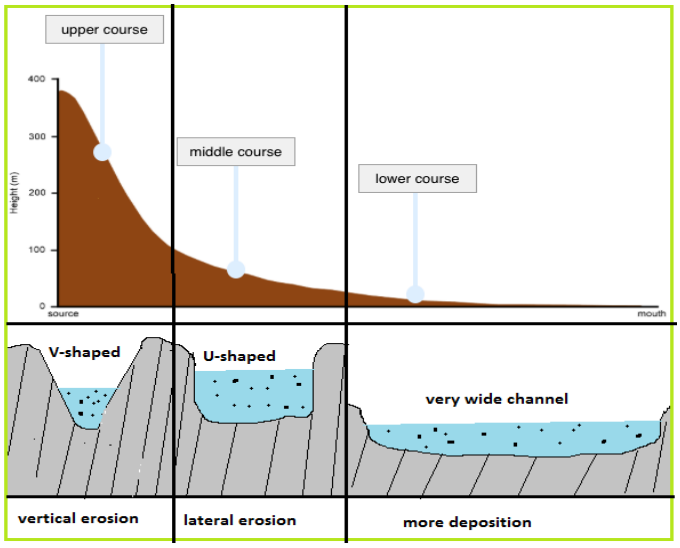
Negative base level change *- occurs when sea level falls in relation to land, or land rises in relation to sea. This movement creates steep gradients along the river resulting in active river erosion. In fact when a negative base level change occurs, knick points are formed which increase the river's erosive power.*

Knick points *are points on a river where there is an abrupt/sudden change in gradient on the river bed. A waterfall is a very good example of a knick point.*

THE CROSS PROFILE OF A RIVER

The river's cross profile refers to the cross-section of a river from one bank to the other. Different factors are responsible for the formation of different cross profiles. These are discussed below in details.

Balance between erosion and deposition - this factor is related to the long profile of rivers. In the upper course of the river there is more vertical incision which leads to the creation of deep narrow valleys that are "V"-shaped.



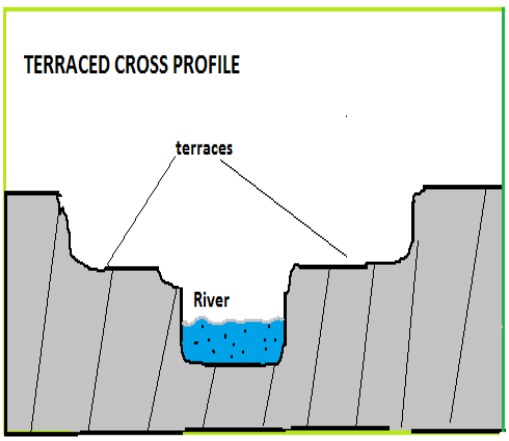
In the middle course, there is more lateral erosion than vertical erosion because the gravitational energy of the river is lower here. Lower gravity results from reduced gradient. Lateral erosion here results in the formation of "U"-shaped channels as shown in the diagram. In addition, since the gradient is becoming gentle, the river will begin to deposit larger materials here leading to reduced river depth and the formation of U-shaped channels.

On the lower course, the gradient becomes very gentle and the erosive power of the river significantly decreases, although the river can still erode laterally (but to a lesser extend). Deposition of sediments is very dominant here. Consequently very wide rivers which are very shallow (not deep) are found here.

Climate - humid climates usually have deep weathered layers that promote both

vertical and lateral erosion. As a result they have wider cross profiles. However, such areas like the tropical might have deep narrow channels because of dense vegetation cover which prohibits erosion by rivers. On the contrary, peri-glacial and glacial regions are likely to have flat-floored cross profiles as a result of glacial erosion. Sub-humid climates promote both lateral erosion and vertical erosion and as a result they have U-shaped cross profiles. Vegetation is sparse and the regolith is fairly deep promoting both lateral and vertical erosion.

Rock type- areas with more resistant rocks/soils e.g. clay tend to have deep narrow channels which are steep-sided because vertical incision is greater than lateral erosion. They actually resist lateral erosion. In addition areas that have got rocks with alternate bands of hard and soft rocks can cause the river to meander as water searches for a weaker rock/path. Meandering creates asymmetrical cross profiles as erosion and deposition occur on opposite banks.



Moreso, areas with layered rocks, e.g. sedimentary rocks, tend to have stepped cross profiles which are also called valleys in valley cross profiles. Mass movements also result in the formation of terraced/stepped cross profiles.

Geological processes- areas that experience tectonic uplift and negative base level changes experience active vertical incision leading to the formation of very deep and narrow river valleys such as gorges. This occurs because tectonic uplift increase the erosive power of the river promoting vertical erosion. Tectonic uplift can also result in the formation of terraced cross profiles.

Faulting- heavily faulted environments are usually associated with nearly vertical valley sides. These steep sided valleys are flat-floored at first but become modified by exorgenic processes like weathering. Reverse faulting often lead to the formation of a terraced cross-profile.

RIVER PROCESSES

The main river processes to be discussed here are erosion, transportation and deposition. Of importance to note is that river erosion and deposition processes lead to the formation of various landforms along rivers' profiles. Erosion landforms include waterfalls, rapids, gorges& potholes, to mention a few; while depositional features include all features of a flood plain, braided channels e.t.c.

RIVER EROSION

Erosion is the wearing away of the river banks and bed or a process whereby water flowing in a channel detaches particles form either the banks or bed of the river and carries them away. A river's load is bits of eroded material, generally rocks that the river transports until it deposits them downstream.

A river's channel is eroded ***laterally*** and ***vertically*** making the channel wider and deeper. The intensity of lateral and vertical erosion is dictated by the stage in the river's course. ***Vertical erosion*** is more pronounced in the upper stage of the river's course (close to the source of the river) and is responsible for deepening the channel. In the middle and lower stages vertical erosion is reduced and more ***horizontal/lateral*** erosion takes place. Lateral erosion is responsible for widening the channel.

In addition, river's channel can be eroded by headward erosion which is responsible for increasing the length of the length of the channel. Headward erosion is when the river wears backwards extending the length of the channel.

There are four (4) ways through which river erosion takes place. These include hydraulic action, corrasion, attrition and corrosion/solution.

Hydraulic action- this is when the sheer force of the water removes rock particles from the bed and banks. This type of erosion is strongest at rapids and waterfalls where the water has a high velocity. It is also more pronounced when the river is in flood or when the river bed is rough. There are two types of hydraulic action which are:

i) Evortion- this involves the direct impact of moving water (weight of water)rubbing against the bed removing particles and carry them. It is responsible for deepening the channel.

ii) Cavitation- is a form of hydraulic action which occurs when air bubbles trapped in the water get compressed into small spaces like cracks in the river's banks and eventually implode creating a small shockwave that weakens the rocks. The shockwaves are very weak but over time the rock will be weakened to the point at which it falls apart.It is responsible for widening the channel and it occurs when water is under very high velocity and when the river bed is irregular.

Corrasion or Abrasion- is when the load being carried by the river strikes/rub against the banks and bed of the channel detaching particles in the process. In other words abrasion is where the river's load acts almost like sandpaper, removing pieces of rock as the load rubs against the bed & banks. This sort of erosion is strongest when the river is transporting large chunks of rock or after heavy rainfall when the river's flow is turbulent.

Corrosion/solution-is a special type of erosion that only affects certain types of rocks. It involves water containing acids or being slightly acidic, reacting with certain rocks and dissolve them. Corrosion is highly effective if the rock type of the

channel is chalk or limestone (anything containing calcium carbonate) otherwise, it doesn't have much of an effect.

Attrition- is a way of eroding the river's load, not the bed and banks. Attrition is where pieces of rock in the river's load knock against each other and further break down into smaller pieces.

RIVER TRANSPORT

This is the downstream movement of sediments either along the channel bed or within the body of water. Energy that remains after the river has overcome friction is used to transport sediments. The amount of sediments carried by the river and the size of these sediments/load depends primarily on the velocity and discharge of the river. At high velocities and when the river discharge is high the river is said to have more energy to transport the load. More sediments are transported when the river is in flood.

There are different ways that a river will transport load depending on how much energy the river has and how big the load is. These include traction, saltation, suspension and solution.

Traction- the largest of particles such as boulders are transported by traction. These particles are rolled along the bed of the river, eroding the bed and the particles in the process, because the river doesn't have enough energy to move these large particles in any other way.

Saltation- slightly smaller particles, such as pebbles and gravel, are transported by saltation. This is where the load bounces along the bed of the river because the river has enough energy to lift the particles off the bed but the particles are too heavy to travel by suspension. In other words river's load is transported in a series of jumps downstream (temporarily lifted by water and bounce along the bed in a hopping manner).

Suspension- very fine particles like clay and silt are transported in suspension, they are suspended in the water. Most of a river's load is transported by suspension.

Solution- is a special method of transportation. This is where particles are dissolved in water and transported in solution. Only rocks that are soluble, such as limestone or chalk, can be transported in solution.

STREAM CAPACITY & COMPETENCE

Rivers can only carry so much load depending on their energy.

Stream capacity- *refers to the maximum volume of load that a river can carry at a specific point in its course OR the ability of a river to transport its load. Stream capacity is influence by velocity, discharge, and gradient of the channel.*

Stream competence- *refers to the biggest sized particle that a river could carry at a specific point. Stream competence is a function of river velocity, discharge, energy,*

and particle size.

NB- the relationship between particle and water velocity is normally illustrated using the Hjulström curve.

RIVER DEPOSITION

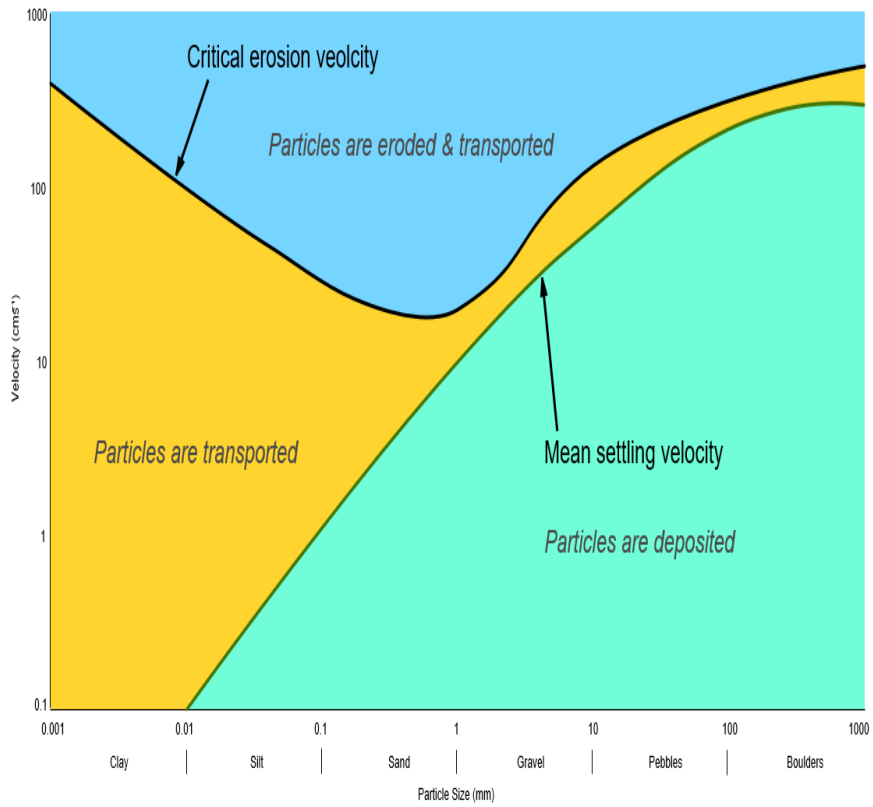
River deposition is the settling of load carried by a river. When a river loses energy it is forced to deposit its load. There's several reasons why a river could lose energy. If the river's discharge is reduced then the river will lose energy because it isn't flowing as quickly anymore. This could happen because of a lack of precipitation or an increase in evaporation. Increased human use (abstraction) of a river could also reduce its discharge forcing it deposit its load.

Deposition also occurs when the velocity of water is low due to reduced gradient especially when the river approaches its mouth (in the lower course). Meandering of a river also lead to deposition on the inner bank. Deposition results in the formation of several landforms as shall be seen later.

If the gradient of the river's course flattens out, the river will deposit its load because it will be travelling a lot slower. When a river meets the sea a river will deposit its load because the gradient is generally reduced at sea level and the sea will absorb a lot of energy.

The Hjulström Curve

A Hjulström curve is a special type of graph that shows how a river's velocity affects it competence and its ability to erode particles of different sizes. There's a lot going on the graph but it's fairly easy to read once you get the hang of it. There's two curves on the Hjulström Curve, a critical *erosion velocity curve* and a mean *settling velocity curve.*



The critical erosion curve shows the minimum velocity needed to transport and erode a particle. The mean settling velocity shows the minimum speed that particles of different sizes will be deposited by the river. The shaded areas between the curves show the different process that will be taking place for particles

that lie in those shaded areas.

As an example, a river flowing at 10cms will transport clay, silt and sand particles but will deposit gravel, pebble and boulder particles. Conversely, a river flowing at 100cms will erode and transport large clay particles, silt particles, sand particles and most gravel particles. It will transport all but the largest of pebbles and will deposit boulders.

The easiest way to read the curve is to draw a horizontal line from the velocity you're trying to read and seeing which shaded area it crosses the particle size you're interested in in. This will tell you whether that particle is eroded, transported or deposited at that velocity.

There's a few interesting things to note about the Hjulström Curve. The first is that clay sized particles don't appear to have a mean settling velocity. This is because these particles are so fine that a river would have to be almost perfectly stationary in order for them to fall out of solution. In addition, the small particles seem to have an erosive velocity that's the same as the velocity for larger particles. This is because smaller particles are cohesive, they stick together, making them harder to dislodge and erode without high velocities.

Strengths of the Hjulström curve

- The graph manages to explain why stream capacity increase in a downstream direction.
- The graph also manages to explain why deposition occurs at each section of the stream's long profile
- It also shows a quantitative relationship between erosion, transportation and deposition.

Weaknesses of the graph

- Sometimes particle size does not correspond directly to the mass of that particular particle
- In some areas deposition has occurred within the channel despite a high stream velocity especially during flooding.

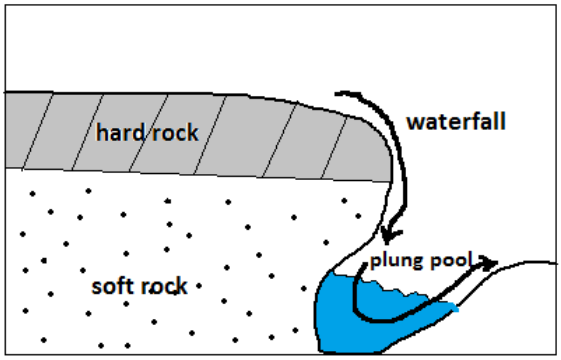
LANDFORMS OF RIVER EROSION

Question: *With the aid of diagrams, describe and explain the landforms resulting river erosion in the upper course of a river.* [12]

WATERFALLS

Waterfalls are found in the upper course of a river. They usually occur where a band of hard rock lies next to soft rock. As the river passes over the hard rock, the soft rock below is eroded (worn away) more quickly than the hard rock leaving the hard rock elevated above the stream bed below.

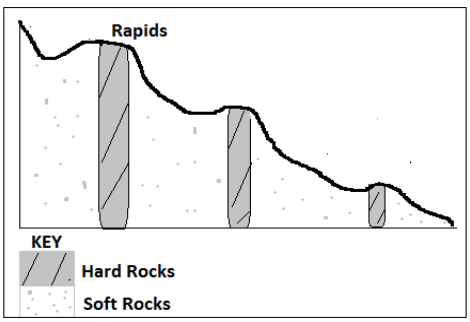
The 'step' in the river bed continues to develop as the river flows over the hard rock step (Cap Rock) as a vertical drop. The drop gets steeper as the river erodes the soft rock beneath by processes such as abrasion and hydraulic action. A plunge pool forms at the base of the waterfall.This erosion gradually undercuts the hard rock until the cap rock is unsupported such that it will eventually collapses. A steep sided valley known as a ***gorge*** is left behind and as the process continues the waterfall gradually retreats upstream. Waterfalls are also formed as a result of uplifting that results in negative base level changes for example the Victoria Falls on the Zambezi River in Zimbabwe.



POTHOLES

Potholes are cylindrical holes drilled into the rocky bed of a river by turbulent high-velocity water loaded with pebbles. The pebbles become trapped in slight hollows and vertical eddies in the water are strong enough to allow the sediment to grind a hole into the rock by abrasion (corrasion). Attrition rounds and smoothens the pebbles caught in the hole and helps to reduce the size of the bed load.

Potholes can vary in width from a few centimetres to several metres. They are generally found in the upper or early-middle course of a river. This is where the valley lies well above base level, giving more potential for downcutting, and where the river bed is more likely to be rocky in nature.



RAPIDS

Rapids develop where alternate bands of hard and soft rocks form part and parcel of the river bed. The soft rock is attacked more quickly by erosion and it is lowered in the process. Bands of hard rocks are left elevated above the lowered soft rocks and these will form rapids

GORGES

Gorges occur on a river flowing along a fault line or line of weakness. Vertical erosion deepens the softer rock leaving resistant rocks outstanding thus creating a narrow deep channel or a gorge. Here mechanical hydraulic action is largely responsible for the formation of the gorge. Gorges are also formed due to the retreat of waterfalls as already highlighted above. A very good example of such gorges is the Naigara Gorge found near Naigara Falls.

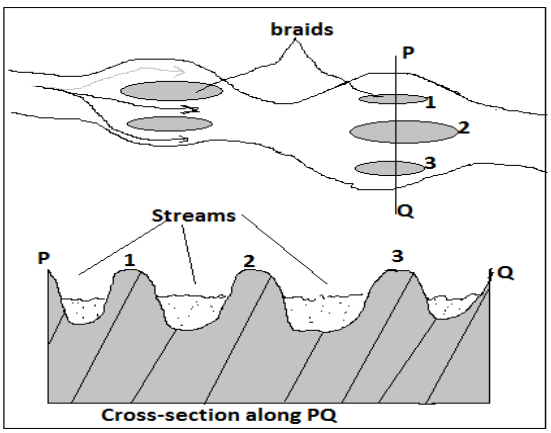
V-SHAPED VALLEYS

These are deep narrow channels formed on the upper course of the river by vertical erosion. They develop here because water has more erosive potential. See diagrams above. Rejuvenation also results in the formation of V-shaped valleys.

LANDFORMS OF RIVER DEPOSITION

BRAIDED CHANNELS

Braiding occurs when the river is forced to split into several channels separated by islands. It is a feature of rivers that are supplied with large loads of sand and gravel. It is most likely to occur when a river has variable discharges for example seasonally humid environments.



They also develop from the middle to lower course where stream competence is lower leading to the deposition of sediments. Deposited sediments accumulate inside the channel forcing the river to split into several channels as shown on the diagram.

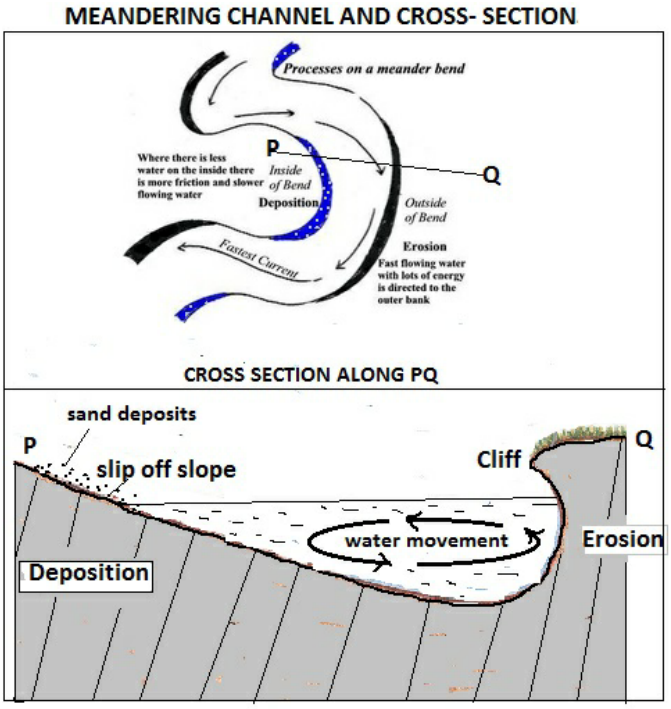
In summary braiding occurs in environments in which there are rapidly fluctuating discharges:

1. Semi-arid areas of low relief that receive rivers from mountainous area and in seasonally humid environments where rainfall is received in summer, causing fluctuations in river discharge.

2. Glacial streams with variable annual discharge. In spring, melt water causes river discharge and competence to increase, therefore the river can transport more particles. As the temperature drops and the river level falls, the load is deposited as islands of deposition in the channel.

MEANDERS

Meandering occurs in the middle course of the river. They usually develop on gentle gradients where the velocity and competence of the river is lower. As a result the river usually avoid obstacles and follow a weaker path thus creating a meander. Both erosion and deposition are active on a meander leading to the formation of river cliffs and slip off slopes.



Water flows fastest on the outer bend of the river where there is less friction. This causes greater erosion which deepens the channel creating a pool near the outer bank of the river.

Lateral erosion is also active here and it results in the undercutting of the river bank and the formation of a steep sided ***river cliff***. In contrast, on

the inner bend water flows at lower velocities hence deposition occurs resulting in a shallower channel.Over time a deposited sediments builds up on the inner bend; resulting in the formation of a slip-off slope. The water in a meander flows in a corkscrew like movement as it moves from the inside of the bend towards the outside of the bend. This is called Helicoidal flow.

Remember - a meander is ***asymmetrical in cross-section*** (see diagram above). It is deeper on the outer bend (due to greater erosion) and shallower on the inside bend (an area of deposition).

OXBOW LAKES

Ox bow lakes are formed on meandering channels as a result of erosion and deposition. As the outer banks of a meander continue to be eroded through processes such as hydraulic action the neck of the meander becomes narrow and narrower.

Eventually due to the narrowing of the neck, the two outer bends meet and the river cuts through the neck of the meander usually during a flood event when the energy in the river is at its highest.

The water now takes itsshortest route rather than flowing around the bend.Deposition gradually seals off the old meander bend forming a new straighter river channel.

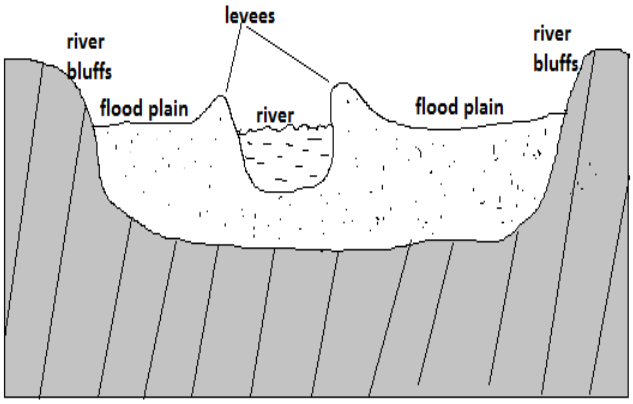
Due to deposition the old meander bend is left isolated from the main channel as an ox-bow lake.Over time this feature may fill up with sediment and may gradually dry up (except for periods of heavy rain). Ox bow lakes can later be turned into rich agricultural units used for the growth of crops. They tend to be very fertile due to alluvial deposition.

LEVEES

In its middle and lower courses,a river is at risk of flooding during times of high discharge. If it floods, the velocity of the waterfalls as it overflows the banks. This results in deposition, because the competence of the river is suddenly reduced. It is usual for the coarsest material to be depositedfirst, forming small raised banks (levees) along the sides of the channel. Subsequent floods increase the size of these banks. Levees can be raised artificially by people inorder to prevent flooding of rivers.

FLOODPLAINS

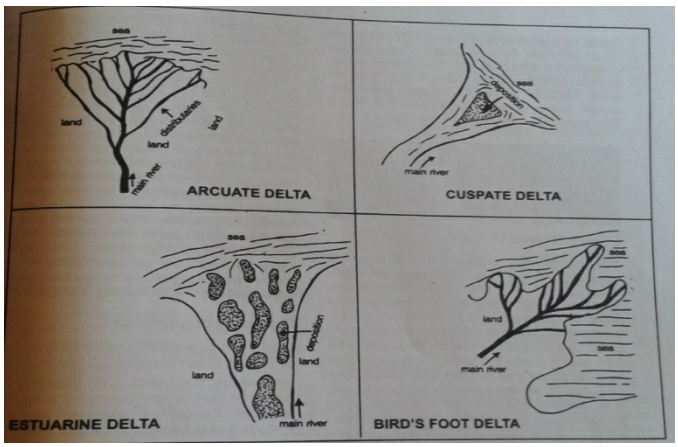
Floodplains are created as a result of both erosion and deposition, although the accumulation of river deposits suggests that they are predominately depositional features.



They are relatively flat areas of land either side of the river and they are composed of alluvium (river deposited silts and clays). Over time, a floodplain can become wider and the depth of sediment accretions increases. The width of the floodplain is determined by the amount of meander migration and lateral erosion that has taken place. Interlocking spurs are also removed by lateral erosion in the middle course, leaving behind river bluffs. The depth of the alluvial deposits depends partly on the amount of flooding in the past, so floodplain creation is linked to extreme events. Flood plains becomestabilised by vegetation over time. They can also be used for agricultural purposes due to the presence of alluvial deposits.

DELTAS

A delta is a feature of deposition, located at the mouth of a river as it enters a sea or lake. Deposition occurs as the velocity and sediment-carrying capacity of the river decrease on entering the lake or sea. Flocculation occurs as fresh water mixes with seawater and clay particles coagulate due to chemical reaction. The clay settles on the river bed.



Deltas form only when the rate of deposition exceeds the rate of sediment removal. In order for a delta to form the following conditions are likely to be met:

· The sediment load of the river is very large, as in the Mississippi and Nile rivers

· The coastal area into which the river empties its load has weak currents. This means that there is limited wave action and, therefore, little transportation of sediment after deposition has taken place. This is a feature of the Gulf of Mexico and the Mediterranean Sea.

Deltas can be described according to their shape. The most commonly recognised is the characteristic ***arcuate delta***, for example the Nile delta, which has a curving shoreline and a dendritic pattern of drainage. Many distributaries break away from the main channel as deposition within the channel itself occurs causing the river to braid. Long shore drift keeps the seaward edge of the delta relatively smooth in shape. The Mississippi has a ***bird's foot delta***. Fingers of deposition build out into the sea along the distributaries' channels, giving the appearance from the air of a bird's claw. A ***cuspate delta*** is pointed like a cup or tooth and is shaped by gentle,

regular, but opposing, sea currents or alongshore.

GEOMORPHOLOGY

Definition *- geomorphology is the study of the earth together with landforms and the processes that lead to the formation of these landforms. It is a systematic study of landforms and the process that forms and shapes them either in the past or present.*

Denudation *- is the total process which explains the wearing down of the earth's surface. It involves various processes such as weathering, erosion, transportation and mass movements. All these processes are therefore broadly known as denudational processes.*

WEATHERING

Weathering *- is the disintegration and decomposition of rocks in situ. Disintegration is the breakdown of rocks by physical means while decomposition is the breakdown of rocks by chemical processes.*

In other words weathering is the mechanical fracturing and decomposition of rocks in situ by natural agents operating on the earth's surface.

THE DIFFERENCE BETWEEN CHEMICAL AND PHYSICAL WEATHERING

PHYSICAL WEATHERING	CHEMICAL WEATHERING
- It is the mechanical disintegration of rocks without any changes in chemical composition of the rock. End products are chemically similar to parent material	- It is the decomposition or rotting of rocks where rocks are altered chemically.
- Produce course textured end products as well as large rock debris such as screes and blocky stones with sharp edges. These end products are unstable which means they can further break down	- Produce fine materials such as clay and sometimes solution. These end products are stable which means they cannot break down any further.

- It is dominant in areas associated with a large diurnal range of temperature with little rainfall amounts e.g. deserts	- It is dominant in hot wet/humid climates such as the tropical rainforest areas because chemical reactions requires water while high temperatures speed up the rate of chemical reactions
- Operates only at the surface being aided by such factors as force, pressure, or heat	- Chemical weathering operates deep within the rock and under the ground as well e.g. humification which leads to the formation of inselbergs under the ground.
- Produce joints and cracks due mechanical stress on rocks	- Operates at crystal level and therefore does not produce cracks and joints

NB- Weathering marks the initial stage of denudation or wearing down of landscape. It loosens materials on slopes that can subsequently transported by such agents as water, wind or ice [erosion].

TYPES OF WEATHERING

There are three main forms of weathering viz. physical, chemical and biological weathering.

PHYSICAL WEATHERING

Physical weathering refers to the mechanical disintegration of rocks by physical means, in which case rocks retain the chemical characteristics of the parent rock. Physical weathering, also known as mechanical weathering, is the class of processes that causes the disintegration of rocks without chemical change. Physical weathering can occur due to temperature, pressure, frost etc.

Plant roots sometimes enter cracks in rocks and pry them apart, resulting in some disintegration; Burrowing animals may help disintegrate rock through their physical action. However, such influences are usually of little importance in producing parent material when compared to the drastic physical effects of water, ice, wind, and temperature change.

Thermal shattering or insolation weathering

Thermal shattering occurs when rocks are exposed to cycles of heat i.e. very hot and very cold temperatures. As a result thermal shattering is dominant in deserts where temperature fluctuations are more pronounced. The main form of thermal shattering is exfoliation.

Exfoliation *occurs when the rock is exposed to heat cycles. Because rocks are poor heat conductors, the outer layers expand and contract faster than the protected*

inner part. Exfoliation is an important mechanism in deserts, where there is a large diurnal temperature range, hot in the day and cold at night. The repeated heating and cooling exerts stress on the outer layers of rocks, causing their outer layers to peel off in thin sheets, exactly the way an onion does.

Exfoliation is described therefore as the peeling away of outer rock layers and it results in the creation of exfoliation domes.

Thermal shattering also occurs on rocks that ***are polymineralllic*** i.e. contains many minerals. Different minerals have different heat absorption capacities hence as some minerals expand more than others, the rock will experience differential stresses that eventually cause the rock to crack apart. This form of thermal stress often leads to granular disintegration whereby rocks weather into smaller grains.

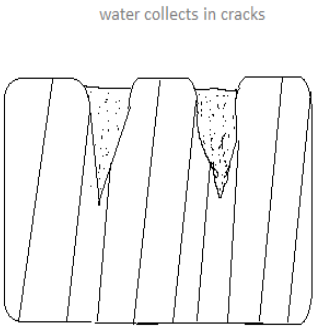
The thermal ***heat from veldfires***can also cause significant weathering of rocks and boulders, heat can rapidly expand a boulder and thermal shock can occur.

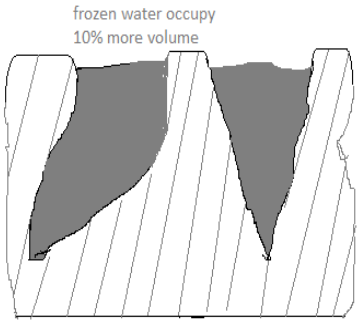
NB- some geologists argue that thermal shattering is minimum in deserts because of lack of moisture to suddenly cool heated rocks. This opinion, is not however not widely accepted.

Frost weathering

Frost shattering is a physical weathering process which involves the action of ice only. Frost shattering is common in mountain areas or in periglacial areas where the temperatures oscillates around freezing point of water. Water collects either in pores or cracks and freeze inside the rock. Frozen water occupy 10% more volume, causing stress and disintegration of rocks. Frost shattering occurs in two ways i.e. ice wedging and ice crystal growth.

Ice wedging- *When water that has entered the joints or cracks freezes, the ice formed strains the walls of the joints and causes the joints to deepen and widen. When the ice thaws, water can flow further into the rock. Repeated freeze-thaw cycles weaken the rocks which, over time, break up along the joints into angular pieces or blocks. The angular rock fragments gather at the foot of the slope to form a talus slope (or scree slope).*





The splitting of rocks along the joints into blocks is called ***block disintegration****. The blocks of rocks that are detached are of various shapes depending on rock structure.*

Ice crystal growth*- This same phenomenon occurs within pore spaces of rocks. The ice accumulations grow larger as they attract liquid water from the surrounding pores. The ice crystal growth weakens the rocks which, in time, break up. It is caused by the approximately 10% expansion of ice when water freezes, which can place considerable stress on the rock.*

Frost shattering occurs mainly in environments where there is a lot of moisture, and temperatures frequently fluctuate above and below freezing point, especially in alpine and periglacial areas. An example of rocks susceptible to frost action is chalk, which has many pore spaces for the growth of ice crystals. This process can be seen in Dartmoor where it results in the formation of tors.

Pressure release or unloading or dilatation

In pressure release overlying materials (the overburden) are removed by erosion, or other processes, exposing buried rocks. Include diagrams here.

Intrusive igneous rocks (e.g. granite) are formed deep beneath the Earth's surface. They are under tremendous pressure because of the overlying rock material. When erosion removes the overlying rock material, these intrusive rocks are exposed and the pressure on them is released. The outer parts of the rocks then tend to expand. The expansion sets up stresses which cause fractures parallel to the rock surface to form. These fractures are called pseudo bedding planes. Over time, sheets of rock break away from the exposed rocks along the fractures, a process known as exfoliation. Exfoliation due to pressure release is also known as "sheeting".

NB- pressure release is also common in deserts due to the removal of the overburden by wind erosion, but mostly in sub-humid environments.

Salt-crystal growth

Salt crystallization causes disintegration of rocks when saline solutions (from dissolved salts) seep into cracks and joints in the rocks and subsequently evaporate, leaving salt crystals behind. These salt crystals expand as they are

heated up, exerting tremendous pressure on the confining rock and leading to its breakdown.

Salt crystallization may also take place when solutions decompose rocks (for example, limestone and chalk) to form salt solutions of sodium sulphate or sodium carbonate, of which the moisture evaporates to form their respective salt crystals.

This process is normally associated with arid climates where high day temperatures causes strong evaporation [dehydration] and therefore salt crystallization. Salt crystallisation often lead to the formation of micro-granitic features such as tafoni and honeycombed rocks along coastal areas.

Differences between granular disintegration and block disintegration

- Block disintegration refers to the breaking down of rocks into large angular blocks or partially broken blocks whereas granular disintegration is the braking down of rocks into smaller fragments or individual grains.
- Block disintegration is wholly a physical weathering process yet granular is physical but sometimes associated with chemical weathering (physio-chemical)
- Block disintegration is mostly active in crystalline rocks like granite while granular is common in porous rocks like sandstone. NB- physical weathering process of ice wedging, root wedging and exfoliation are largely responsible for the process of exfoliation.

CHEMICAL WEATHERING

Chemical weathering is the decomposition or decaying of rocks that removes the natural cements holding the rock together. It changes the composition of rocks, often transforming them when water interacts with minerals to create various chemical reactions. Chemical weathering is enhanced by the presence of moisture [high rainfall] as well as high temperatures [temperature is needed to speed up chemical reactions].

Carbonation and solution

Solution weathering- this is the dissolving of minerals in rocks when they combine with water. The rate of solution weathering is determined by the pH value of the water. If acids are present in rain water (Acid rain), then more minerals become soluble thus increasing solution weathering. Acid rain occurs when gases such as sulphur dioxide and nitrogen oxides from fossil fuel burning and industriesare present in the atmosphere. They react with rainwaterwater to produce stronger acidswhich can cause solution weathering to the rocks.

Carbonation- is a typical example of solution weathering. Carbonation occurs whenrain combines with carbon dioxide or an organic acid to form a weak carbonic acid as shown in the following reaction:

$$CO_2 + H_2O \rightarrow H_2CO_3$$ [Carbon dioxide + water → carbonic acid]

Carbonation is common in rocks which contain calcium carbonate, such as

limestone and chalk. In this case the carbonic acids reacts with calcium carbonate (the limestone) and forms calcium bicarbonate as shown in the following reaction:

Carbonic acid + calcium carbonate → calcium bicarbonate

This process speeds up with a decrease in temperature, not because low temperatures generally drive reactions faster, but because colder water holds more dissolved carbon dioxide gas. Carbonation is therefore common in cold climates like peri-glacial and temperate regions, where water is available.Carbonation on the surface of well-jointed limestone produces a dissected limestone pavement. This process is most effective along the joints, widening and deepening them.

Hydration

Hydration is a chemical weathering process which occurs when rocks absorb water and expand or increase in volume. This expansion set up physical stress within the rock leading to its breakdown. When dehydration occurs, the rock loses water and shrinks. This process is more of a mechanical wetting and drying process but becomes chemical because there is a rigid attachment of hydrogen ions of water to the atoms and molecules of a rock mineral (bonding).

For example oxides are converted to iron hydroxides and gypsum becomes a hydrate when wet. In conclusion, it is widely accepted that hydration is a physic-chemical weathering process.

Hydrolysis

Hydrolysis is a chemical weathering process which involves water strictly. It is a reaction in which water reacts with rock minerals that contain cations. In such reactions hydrogen ions replace cations present in rock minerals and chemically reduce them [a process called cation exchange]. For example feldspar in granite rocks react with water to produce clay minerals.This hydrolysis reaction is much more common.

Oxidation

Oxidation takes two processes, i.e. addition process and reduction process.

Addition process- occurs when oxygen in the atmosphere or in water oxidises rock minerals for example the oxidation ferrous iron (which is blue-grey in colour) to become ferric iron. This gives the affected rocks a reddish-brown coloration on the surface which crumbles easily and weakens the rock. This process is better known as 'rusting', though it is distinct from the rusting of metallic iron.

Reduction process- in reduction process rocks loose oxygen which means reddish coloured rocks turns back to blue – grey colour. NB oxidation is effective in attacking iron compounds which frequently act as cementing agents in sedimentary rocks.

Biological weathering

Plants and animals may lead to both chemical and physical weathering in a number

of ways.

Lichens and Mosses - Lichens and mosses grow on essentially bare rock surfaces and create a more humid chemical microenvironment. The attachment of these organisms to the rock surface enhances physical as well as chemical breakdown of the surface micro-layer of the rock.

Root wedging – Occurs when plant roots grow inside the joints and rock crevices, exerting mechanical pressure in the process. Here tree roots force apart the joints and cracks although this process cannot be equivalent to thermal shattering and frost action. This process also provides a pathway for water and chemical infiltration, thus increasing the rate of chemical weathering.

Chelation– is the most common form of biological weathering which involves the release of chelating compounds(i.e. organic acids) by plants. Chelation occurs when humic acids formed by the reaction between water and humus (decayed remains of dead plants) increase the solubility of minerals thus causing chemical weathering.

Chelation promotes deep weathering and is therefore responsible for the formation of sub-aerial weathering products like inselbergs.

Barrowing animals – small creatures like worm, rabbits, e.t.c also plays a role in the weathering of rocks. However, their impact on weathering is less compared to the action of plants.

Differences between exfoliation and spheroidal weathering.

- Exfoliation is typically a physical weathering process yet spheroidal is a chemical weathering process.
- Exfoliation occurs at the surface [surface process] while spheroidal weathering is a sub-surface process.
- Exfoliation is common in dry climates like deserts yet spheroidal weathering is common in hot humid climates.
- Exfoliation typically occurs in intrusive igneous rocks like granite when they are exposed to repeated heating and cooling from the sun but spheroidal weathering occurs when water enters cracks and joints just below the surface, causing weathering which will tend to round the blocks off - hence spheroidal (corners have more surface area than flat surfaces, so they weather out faster, leaving a rounded edge.)

Spheroidal weathering is a form of chemical weathering that affects jointed bedrock and results in the formation of concentric or spherical layers of highly decayed rock within weathered bedrock that is known as ***saprolite****. When saprolite is exposed by erosion, these concentric layers peel off as concentric shells much like exfoliationhence spheroidal weathering is also called onion skin weathering.*

FACTORS AFFECTING THE RATE AND TYPE OF WEATHERING

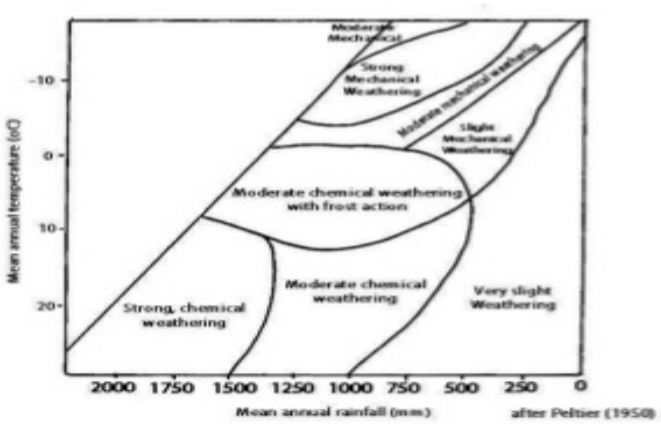
Factors affecting the rate and type of weathering are grouped into three i.e. climate, lithological factors and site factors. These are discussed fully below:

CLIMATIC CONDITIONS

Climate dictates the rate and type of weathering processes that operate, largely by determining the amount of water available, vegetation cover and the temperature at which the processes occur. In summary, there is more chemical weathering and less physical weathering in hot humid environments while there is more physical and less chemical in arid and semi-arid environments. The effect of climate on weathering is described in Peltier's model.

PELTIER'S MODEL

The model was forwarded by L.C Peltier in 1950. Peltier argued that there is high possibility to accurately predict the type and the intensity of weathering predominant in any part of the world given the prevailing climate conditions. He believed that physical and chemical weathering processes are controlled by the main climate variables of temperature and rainfall. See diagram below:



According to Peltier intense chemical weathering occurs mainly in hot humid climates where rainfall and temperature are high throughout the year. Physical weathering, mainly in the form of frost shattering is common in peri-glacial regions where temperatures oscillates around freezing point. Physical weathering is also dominant in arid and semi-arid environments where little rainfall limits chemical weathering.Lastly, Peltier argued that there is limited insolation weathering in hot humid environments because there sky is always overcast hence limiting insolation weathering.

Applicability of Peltier's model

The climate oriented zones forwarded by Peltier can be supported by observing dominant weathering processes in different climate zones. His arguments are relevant in most climate zones.

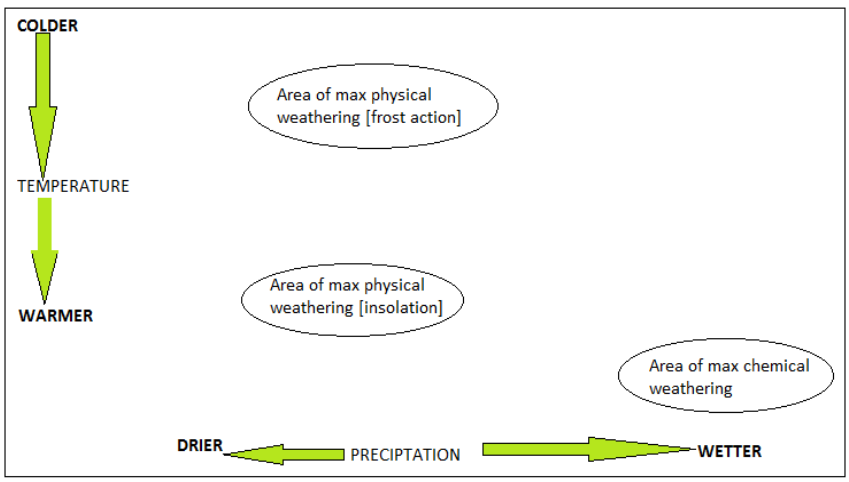
Limitations of the model

- The model doesn't recognise other factors except climate which influence the type and intensity of weathering on a local or small scale. Such factors include altitude, aspect, and rock characteristics.

- The limited occurrence of exfoliation in hot humid environments as argued by Peltier is highly questionable. According to Peltier's model the moist the area becomes, the denser the vegetation becomes thus limiting the effectiveness of insolation weathering. However, looking at the Savana regions, the sparse distribution of vegetation allow effective insolation leading to intense exfoliation on landforms such as inselbergs and dwala [ruwares].
- The model does not consider the relationship between chemical and physical weathering. In most cases, physical weathering results in the formation of small rock fragments known as screes or talus. These fragments are further downsized into smaller soil particles by chemical weathering. This therefore implies that chemical and physical weathering complement each other. This is evidenced by the presence of decomposed rock particles at the foot of exfoliation domes.
- Peltier's arguments seem to be based on observations made in the peri-glacial regions and hence have little applicability in other climatic regions. For instance he did not consider seasonal variations in temperature and rainfall in sub-humid environments where intense chemical weathering occurs in the wet season followed by intense physical during the winter, dry season [in the form of exfoliation, pressure release and frost action].
- Chemical weathering is also thought to be occurring at a faster rate in hot deserts as a result of infrequent, erratic or spasmodic storms which provides moisture in contrast to earlier beliefs which showed that there is little chemical weathering occurring in deserts.
- Lastly, it is generally accepted that the model lacks field measurement and hence cannot be considered as a comprehensive model.

WAUGH'S MODEL

D. Waugh (1985) developed a model similar to that of Peltier. His model tries to correct some of the problems associated with Peltier. See diagram below:



Waugh noted that there is maximum physical weathering in two climatic zones, i.e. (i) the cold and relatively dry regions associated with high rates of frost action and (ii) the hot, dry regions (deserts) associated with high rates of insolation weathering.

He also observed that chemical weathering is more intense in hot humid

environments since a combination of high rainfall and high temperature is crucial for chemical reactions to occur. In addition the presence of dense vegetation in such climate zones promote rapid decomposition of rocks by humification process.

Question: Show how climate influence the rate and type of weathering. [12]
Climate dictates the rate and type of weathering processes that operate, largely by determining the amount of water available, vegetation cover and the temperature at which the processes occur. In summary, there is more chemical weathering and less physical weathering in hot humid environments while there is more physical and less chemical in arid and semi-arid environments.

Equatorial climate or humid tropical regions:
Equatorial climates are characterised by high temperatures and high rainfall throughout the year [hot humid conditions] and as such chemical weathering processes are dominant here. Moisture is essential for chemical reactions while high temperatures speed up the rate of chemical reactions. The humid conditions in tropical rainforest areas thus provide optimum conditions for the occurrence of chemical weathering at a much faster rate.

In addition, equatorial climates are characterised by dense vegetation cover because of high rainfall. As a result there is more litter which tend to be decomposed and produce humic acids which promote the process of chelation. Sub-areal chemical weathering is thus dominant in these areas leading to the formation of very deep regolith (30 to 60 m deep).

In contrast, physical weathering is slow in equatorial climate because the sky is overcast most of the time. Moreso, the presence of dense vegetation cover mask rocks and reduce the effectiveness of insolation weathering.

Sub-humid tropical regions/ Savanna {tropical continental}:
These areas have two distinct seasons, i.e. the hot wet summer and the cold dry winter. As a result they experience both physical and chemical weathering but at moderate levels.

During the summer season, high temperatures and high rainfall provide optimum condition for chemical weathering. Vegetation will also be dense during this period leading to more humification but less insolation weathering.

In contrast, the winter season experience maximum physical weathering because low vegetation cover expose rocks to the effect of insolation weathering. Frost shattering is also dominant due to low temperatures during this period. Erosion is very more pronounced in this climate due to limited regolith cover.

Erosion actively removes weathered debris thus exposing new weathering surfaces and increasing the rate of physical weathering. Lack of moisture in winter slows chemical weathering. However, regolith is shallower compared to that of equatorial climate.

Arid and semi-arid regions:
These environments are characterised by very low rainfall totals and a large diurnal

temperature range [high day temperatures and low night temperatures]. As a result deserts experience rapid physical weathering in the form of exfoliation, salt crystallisation and pressure release. High temperatures promote dehydration and salt crystallisation while heat cycles lead to exfoliation. Pressure release is promoted by rapid removal of the overburden by both water and wind erosion. Lack of vegetation cover also promote insolation weathering since rocks are not masked or covered.

On the contrary, chemical weathering is slow in deserts due to lack of moisture. Chemical weathering only occurs slowly as a result of erratic storms which are sometimes received. Consequently desert soils have very shallow regolith.

Temperate regions:

Are characterised by moderate temperature within a range of 10-20^{0}C and moderate annual rainfall between 500 and 1000mm. During winter snow is common leading to freeze-thaw action. Chemical weathering is also active particularly oxidation and carbonation. Carbonation becomes more intense at low temperatures.

Glacial and Peri-Glacial regions:

They are characterised by the presence of ice sheets, ice caps and glaciers which to a larger extent mask rocks and prevent/slows weathering. Frost weathering is common in rocks protruding above these ice sheets. Slight increase in surface temperatures lead to the thawing of ice in cracks and further increase the effect of frost shattering.

While chemical weathering is minimum here due to low temperatures, carbonation can occur since water derived from thawing snow contains high proportions of dissolved carbon dioxide.

LITHOLOGICAL FACTORS

ROCK TYPE:

Determines the resistance of the rock to the weathering processes that operate in that particular environment. Each rock type is composed of a particular set of minerals, which are joined together by crystallisation, chemical bonding or cementing. The effect of rock type on the type and intensity of weathering is observed by looking at hardness, age, mineral composition and jointing.

(i) *Rock hardness or strength*- granite rocks are very hard and therefore resist weathering as compared to other rocks like limestone. The hardness in granite rocks is caused by the fact that it is an igneous rock composed of numerous crystals (e.g. feldspar and quartz) which are bound together during formation. These individual crystals are very hard making granite rocks more resistant to weathering.

Another factor that influence rock hardness is age. Generally older rocks become very hard and more resistant to weathering. However, rock

hardness does not entirely prevent weathering of rocks since the presence of fractures can force the rock to break down depending on other prevailing conditions.

(ii) *Mineral composition*- Minerals are solid substances found within rocks that have their own distinct chemical composition. The chemical nature of rocks determines the intensity of weathering of rocks since different minerals have different vulnerability to chemical change. For instance, limestone rocks which contain calcium carbonate are easily attacked by carbonation. Granite rocks, on the other hand, contain three minerals which vary in terms of vulnerability to weathering. Quartz and mica are more resistant than feldspar hence feldspar would be weathered faster under humid conditions to produce clay.

Minerals that give rocks dark colours e.g. gabbro, basalt; have more heat trapping capabilities hence are more vulnerable to physical weathering processes.

(iii) *Rock joints and bedding planes*- A joint is a fracture of natural origin found in a rock. Rock joints are caused by various geological processes occurring on or under the earth's surface. These are listed below:

- **Exfoliation** – are joints that develop when rocks are exposed to heat cycles. Rocks are poor conductors of heat hence when heated, the outer layer expand faster creating sheet joints in a process called sheeting. Vertical joints are created when temperatures drop rapidly forcing the rock to contract. Repeated heating and cooling of rocks results in the formation of massive sheet joints in rocks.
- **Pressure release/unloading** – are joints formed when buried rocks are exposed to the surface by denudational processes of erosion and weathering. Under the ground rocks are at tremendous pressure hence when exposed, they expand and produce curvilinear sheet joints or pseudo bedding planes.
- **Cooling joints** – are joints formed during the solidification of magma under the ground (in granite rocks) or at the surface when lava solidifies. These joints develop due to stress during cooling of rocks.

Bedding planes are lines or junctions separating individual layers of

sedimentary rocks. Bedding planes are common in rocks such as limestone and chalk.

The presence of rock joints and bedding planes increase the surface area for weathering such that well-jointed and well-bedded rocks are associated with intense physical and chemical weathering. Joints also increase the rate of chemical weathering by allowing weathering agents to enter the rock. This explains why limestone rocks are more vulnerable to chemical weathering.

In addition, rock joints are utilised by the process of frost shattering and salt crystallisation. This facilitates physical weathering. Root wedging also take advantage of rock joints.

Difference between granite rocks and limestone rocks

- Granite rocks [a class of igneous rocks] are formed due to the solidification of magma slowly under the ground yet limestone rocks [a class under sedimentary rocks] are formed when fragments are deposited in layers and cemented in a process called sedimentation.
- Granite rocks are very hard compared to limestone rocks. This means that granite rocks are impermeable while the soft sedimentary rocks are porous.
- Granite rocks are crystalline which means they can be weathered into blocks by block disintegration yet limestone rocks are non-crystalline hence can be weathered into smaller grains (granular disintegration).
- Limestone rocks have more joints while granite rocks only have pseudo/fake joints.
- Granite rocks have 3 important minerals i.e. feldspar, mica and quartz yet limestone rocks have 80% calcium carbonate.
- Granite rocks are mainly weathered physically but limestone is more vulnerable to chemical decomposition or rotting.

SITE FACTORS

Slope angle and altitude- physical weathering processes such as exfoliation largely depends on the rate of removal of weathered debris by mass movement and other transportation processes. The quick removal of weathered debris particularly on steep gradients expose fresh layers of rocks thus increasing weathering rate. Consequently, exfoliation is greatest on steep escarpments where rock falls and landslides are common. Frost action is greatest on higher altitudes typically on mountain tops due to low temperatures there. On the other hand chemical weathering tend to be greatest at the basements of hills due to the accumulation of moisture there.

Vegetation type and density- vegetation cover is a function of climate. Areas with dense vegetation cover are associated with intense chemical weathering due to the availability of humus [humic acids]. Vegetation also opens up the pore spaces in the soil, thus allowing moisture to enter rocks underground. Lastly dense

vegetation promote the process of root wedging. However, vegetation covers rocks and therefore lowers radiation intensity and insolation weathering.

On the contrary, areas with less vegetation cover are associated with intense physical weathering as rocks are left bare and prone to the effect of insolation. However, this effect depend on other prevailing conditions.

DEEP WEATHERING

Definition: deep weathering is a process which describes the formation of deeply weathered layers or saprolite by sub-aerial chemical weathering process. These deep saprolites are formed when chemical weathering exceeds the rate of stripping of weathered debris. Where chemical weathering exceeds the rate of removal due to dense vegetation cover and favourable slope gradient deep weathered layers of up to 60m are created.

Where chemical weathering is equivalent to the rate of stripping off of saprolite, the depth of regolith is constant. Disturbances of surface conditions by people e.g. through deforestation can increase the rate of stripping of regolith thus reducing the depth of regolith.

Saprolite- refers to the finely weathered rock debris which is produced mainly by chemical weathering processes which lies in its original position. In other words saprolite refers to the surface of deeply weathered igneous rock or metamorphic rock, rich in clay minerals. It is typically formed in the warm humid and sub-humid environments. Saprolites form in the lower zones of soil horizons and represent deep weathering of the bedrock surface.

Regolith- refers to a deep layer of fine and partially weathered rock debris accumulated over many years of sub-aerial chemical weathering but not necessarily lying in its original position. Regolith may form as a result of residual accumulation of weathered material or as a result of a combination of sub-aerial weathering and deposition of fine and course material by running water.

Rice (1943) described regolith as a general or umbrella term for denudational products including weathering and deposition.

Basal surface of weathering or weathering front- refers to the boundary between weathered and fresh rocks, it shows the maximum depth at which weathering can take place. It tends to be irregular in outline.

According to Mutodi E. basal surface of weathering refers to the rising and falling bedrock surface overlain by weathered rock debris on which perhaps the absence of rock joints prohibits further chemical weathering. In short BSW refers to the boundary between weathered and unweathered rocks

Denudation- is the long-term sum of processes that cause the wearing away of the Earth's surface leading to a reduction in elevation and relief of landforms and landscapes. It involves weathering, erosion, transportation and mass movements.

FACTORS AFFECTING DEEP WEATHERING

Factors affecting deep weathering are classified as climatic, biotic, geomorphological, and chronological factors.

Climatic factors

Hot humid environments receive high rainfall [above 1300mm/year] and high temperature [27^0C on average]. These conditions yield a great deal of sub aerial decomposition of rocks. On the contrary, limited rainfall in the sub-humid environments reduce the rate of sub-aerial chemical decomposition of rocks. In fact this process is dominant only during the wet season when both rainfall and temperatures are high. Desert climates experience minimum rates of deep weathering due to absence of moisture.

Biotic factors

The amount of vegetation cover is mainly a function of climate. Equatorial climates are characterised by dense vegetation cover which provide more organic acids during decomposition. This gives rise to the process of sub-aerial chelation process. In addition, dense vegetation cover protect saprolite from erosion which could result in the stripping of regolith. Lastly, vegetation increase water seepage which means that chances of deep weathering are high.

On the contrary, sub-humid environments are characterised by dry spells which reduce vegetation cover thus limiting sub-aerial weathering. The temporary removal of vegetation also promote the stripping of regolith resulting in shallow weathered layers.

Geomorphological factors

These are related to the conditions of tectonic stability or instability as well as the age of the landscape where deep weathering occurs. Uplifting or base level change promote rapid downcutting, increasing the rates of erosion (stripping of regolith) and as such tend to reduce deep weathering. See the effect of tectonic uplift on rivers. On the contrary, stable landscapes such as those associated with graded river profiles tend to experience a cumulative accumulation of regolith increasing the depths of weathered regolith.

Chronological factors

These are time-related factors which include climate change and tectonic changes. Climate change results in an alteration of balance between the processes resulting in regolith accumulation [weathering and deposition] and the processes leading to its removal [erosion and transportation]. In deserts for example, the remnants of deep weathered layers were formed during the past wetter episode. However the subsequent drought conditions that followed resulted in high levels of erosion [wind and water] and the removal of deep weathered layers.

Site or environmental factors

Deep weathering occurs rapidly on elevated sites experiencing free drainage. The rapid removal of rain water on such sites tend to reduce water logging thus

promoting chemical weathering. However, it must not be dismissed that chemical weathering requires an abundant supply of moisture. Hence reception areas, experiencing convergent runoff have more chemical weathering due to abundant water supply, although the rates tend to be low due to poor drainage.

Geological factors

The predominance of rocks with minerals prone to chemical attack tends to promote deep weathering. Different rock types have different mineral combinations making their vulnerability to chemical weathering different. For example feldspar in granite rocks is more vulnerable to chemical attack under humid conditions while quartz is more resistant under similar conditions. Sandstone have large grains and a crystalline structure making it subject to rapid chemical decomposition. Well jointed rocks also promote rapid chemical attack.

DEVELOPMENT OF DEEP WEATHERED LAYERS

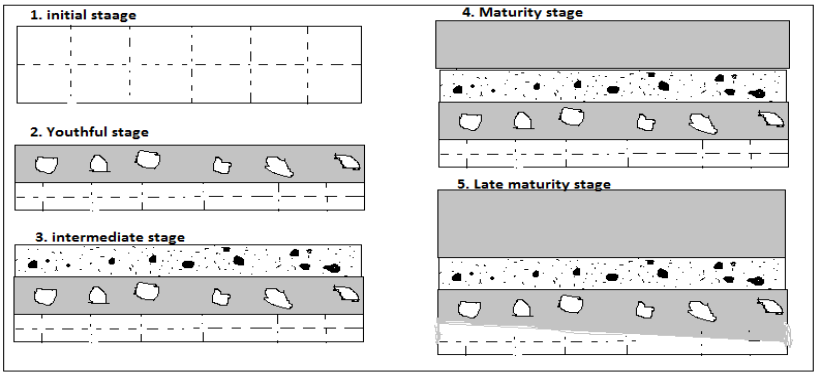
Deep weathered layers over thousands, perhaps millions of years as a result of sub-aerial chemical weathering. Ruxton and Berry developed a time-dependent model to explain the development of deep-weathered layers.

The Ruxton and Berry Model

Ruxton and Berry (1975) argued that the development of deep weathered layers is time-dependent. They also argued that the decomposition of granite resulted in the formation of ***four layers*** or weathering zones underlain by a weathering front (basal surface of weathering).

- The first layer or zone consists of *finely weathered clay particles (fine residual saprolite)* resulting from a complete decomposition of rocks.
- Zone 2 comprises of both *residual debris or saprolite and some small rounded rock fragments*, perhaps resulting from the weathering of resistant silicate compounds.
- Zone 3 comprises of *a mixture of partially weathered core stones and residual debris.*
- Lastly, zone 4 comprises of *weakened or partially weathered blocks* whose joints have just been opened up. Beneath zone 4 is the weathering front.

Ruxton and Berry also argued that where the four zones occur in a single profile, they indicate a mature stage of chemical weathering achieved over many years. See diagrams below:



In the initial stage, exposed granite rocks are attacked by chemical weathering processes producing

debris of zone 3 and 4. This is followed by successive development of other zones until the final maturity stage is reached. This is however achieved over many years of chemical decomposition of rocks.

LANDFORMS ASSOCIATED WITH GRANITE REGIONS

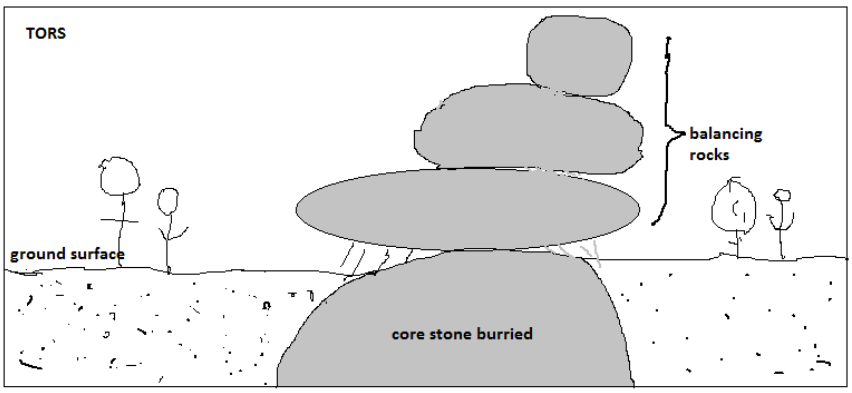
TROPICAL INSELBERGS

The term Inselberg refers to a variety of steep-sided isolated residual hills of solid rock, rising abruptly from a plain of low relief. Inselbergs are often associated with sub-humid environments where the stripping of regolith is rapid. They are also called 'island mountains' and results from the weathering of granitic rocks.

TYPES OF INSELBERGS

TORS

Tors can be described as spheroidally weathered boulders rooted in the bedrock which has been exposed by the process of exhumation.

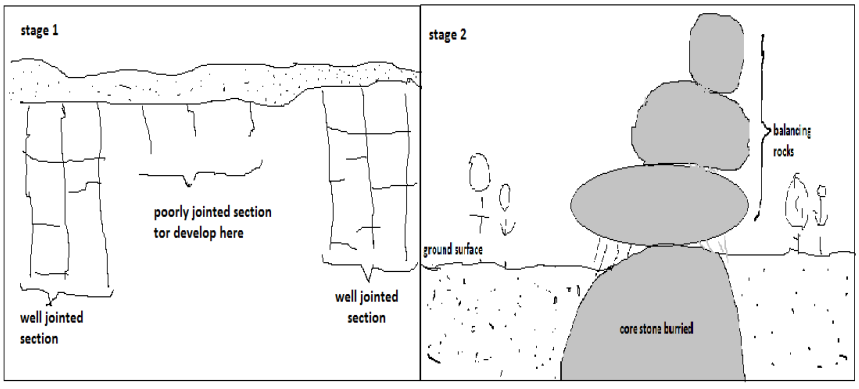


Tors should not be confused with castle kopjes although they are both balancing rocks. Unlike tors, castle kopjes are blocky structures of granitic rocks formed by as a result of sub-aerial joint collapse.

THEORIES OF TOR FORMATION

i) *Linton's hypothesis*

Linton (1955) suggested that tors are formed mainly as a result of deep withering involving the breaking down of irregular jointed rocks. According to this theory, granite rocks have uneven joints with some sections having closely packed joints and others being poorly jointed. The well jointed sections weather faster while poorly jointed sections weather slowly forming rounded core stones showing the spheroidal weathering. See diagrams below:



Linton argued that the

sub-humid environment which is characterised by two distinct seasons is ideal for the formation of tors. This is because in summer, deep chemical weathering is promoted. On the contrary temporary loss of vegetation in winter and during the early months of summer promote rapid stripping of regolith. Linton's hypothesis is well exemplified in Chitungwiza where tors form a continuous range resulting from uniform surface erosion. This theory is the most comprehensive and widely accepted one.

ii) *The periglacial theory*

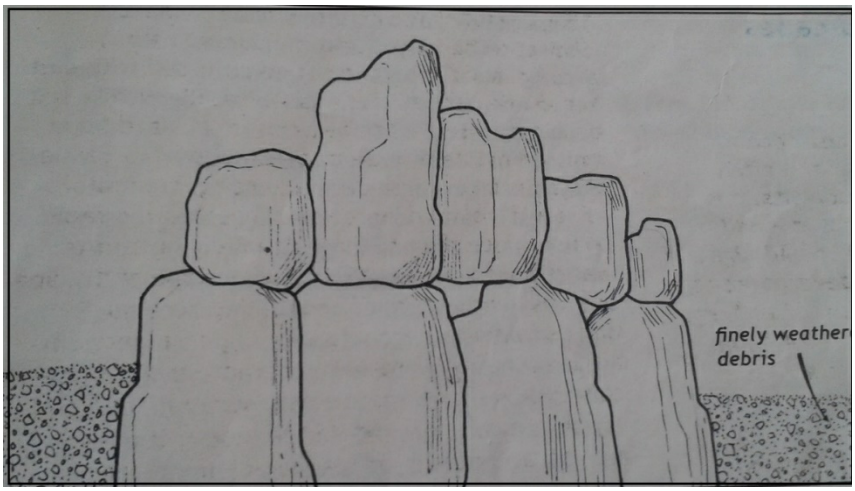
Proponents of this theory (Nelson and Palmer 1962) believe that tors are formed as a result of the process of block disintegration in periglacial regions. They believed that tors are formed as a result of frost shattering whereby water freezes inside cracks and solidifies there causing block disintegration on gentler slopes and tors on steeper ones. However the theory fails to explain the formation of tors in the sub-humid tropics and in other warmer climates.

iii) *The pediplanation theory*

This theory was proposed by LC King (1948). He proposed that tors are formed by the same processes resulting in the formation of Pedi-plains found in most parts of Africa. According to King, tors are exposed by the uniform removal of weathered debris by surface erosion during scarp retreatment and pediment extension process. Tors are also formed when pre-existing bornhardt domes break down.

CASTLE KOPJES

Castle kopjes are blocky looking mountains which sometimes resemble scale tors. They have rectangular boulders from decaying rocks. Curvilinear and vertical joints are visible in castle kopjes.



The Etchplanation or exhumation theory of Inselberg formation

The theory was proposed by Falconer (1911) and later adapted by Willis (1936),

Wayland (1934) and Thomas (1974). According to the theory, inselbergs are formed when the weathering front is exposed as a result of the stripping of regolith or exhumation by surface erosion. The theory suggest that an episode of deep weathering is followed by stream downcutting and stripping of weathered debris.

The process is dominant in sub-humid tropics where deep weathering and stripping occurs in an alternate fashion. The wet hot summer favours deep weathering while the temporary removal of vegetation in winter promote stripping of regolith or exhumation.

Strengths of the theory

- The site of inselbergs favours an Etchplanation origin, for example in Zimbabwe most inselbergs are found in communal areas where surface erosion is rapid due to widespread removal of vegetation cover. There are slim chances of finding inselbergs in commercial farms where effective soil conservation methods are in place.
- The process manages to explain the development of various forms of inselbergs like tors, and castle kopjes.

Weaknesses of the theory

- According to R.J. Small the immediate problem with the Etchplanation theory is the great height of up to 300m associated with some tropical inselbergs. However R.J Small accepted that the height could be a result of several episodes of weathering and erosion over many years.

Briefly describe the characteristics of granite and explain its impact on the way it is weathered. (12m)

Chemical Composition: Chiefly made of quartz, orthoclase feldspars and biotite micas. Although relatively stable, hydrolysis can wear down feldspars and micas to kaolin, if water is provided entry into the granite.

Hardness: Very hard, (especially due to the presence of quartz), providing mechanical strength. This characteristic allows some resistance to weathering. However, presence of joints could decrease resistance.

Texture: Course grained, large crystal size (3-5mm), however, minerals interlocked tightly, therefore decreasing porosity, and increasing resistance to weathering.

Colour: Varies, from light to dark. Dark colours, however, with lower albedo encourages the absorption of light. Alternative heating and cooling results in expansion and contraction of the granitic rock, inducing stress and resulting in insolation weathering. *The effect also occurs when the rock is made of different coloured minerals, different grains would expand and contract alternatively, which

would lead to granular disintegration.

Permeability: Poor primary permeability as minerals interlocked tightly. However, extensive presence of joints (secondary permeability). Joints develop during cooling when it contracts, developing in 3 main directions, vertical, horizontal and curvilinear (due to pressure release). Jointing makes granite vulnerable to physical and chemical weathering, as it allows for entry of weathering agents such as water, and increases the surface area for weathering.

Discuss the necessity of a seasonal humid tropical climate for the formation of inselbergs. (13m)

A seasonal humid tropical climate is necessary to a large extent in the formation of inselbergs. According to the Etchplanation theory of formation, inselbergs require a period of humid tropical climate followed by a period of aridity. It is during the humid climate when intense deep and differential chemical weathering takes place and intense erosion and exhumation will take place during the period of aridity, thus allowing for the formation inselbergs. Therefore, it being 'seasonal' plays a very important task in the formation of the inselbergs.

Firstly, the geological conditions required are the presence of differential joints in order to form tors, ruwares, bornhardts or kopjes. To form tors, jointing should be more cuboidal and extensive, while the rock is usually more massive for the formation of the other types of inselbergs.

The first stage, according to the Etchplanation theory, involves the deep and differential weathering where those areas with close network of joints undergo greater weathering and to greater depths relative to those with widely-spaced joints. In this case, such intense chemical weathering will include hydrolysis and hydration. These weathering processes require the water from rainfall derived from the humid climate. When the rock is eventually weakened chemically, physical exertion would help in its disintegration. Weathering extends all the way to the basal surface of weathering, hence the basal platform is irregular with rises and troughs due to the uneven distribution of joints. The rises are the areas which have undergone a lesser degree of weathering. In the formation of tors, the lower parts usually preserve rounded, detached boulder or course of unweathered rock. However, in the formation of the other inselbergs, the extent of weathering is less and still maintains the massiveness of the original granite rock.

However, regolith now overlies the troughs and does not uncover the inselbergs yet. Thus, the humid climate is required only to an extent of its formation, and has to be seasonal. To complete the process, a period of aridity is required for the erosion and exhumation of regolith to reveal the inselbergs finally.

The exhumation will take the form of river erosion, incision, wind erosion and surface erosion. The first condition required for exhumation is during rapid uplift and incision of streams. Vertical downcutting of streams would result in the removal of regolith. Incision of the regolith occurs as a result of the climatic change to an arid one, with open vegetation cover and a more rapid hill slope erosion. The loss of vegetation cover as a result of a drier climate implies the loss or soil

nutrients which binds regolith. The loss of vegetative cover also implies higher rates of rain splash and gully erosion. The rate of surface wash erosion is also accelerated due to lack of veg. Wind erosion is significantly high due to high wind speed in arid climates, being loose and unconsolidated, regolith will be easily removed.

This process causes piles of corestones to be exposed, in the formation of tors, and the greater portion of the basal surface of weathering to be exposed, in the formation of the other inselbergs. When only a limited amount of regolith is removed, then only a small section of the summit of the rises would be exposed, this is known as the ruwares. A bornhardt is exposed when more layers of regolith are exposed by weathering agents like insolation, acquired in an arid region. The removal of regolith also results in pressure release which leads to the formation sheet and curvilinear joints, further disintegrating the granite into kopjes.

Therefore, a "seasonal" humid tropical climate is highly necessary for the formation of inselbergs as there is also a need for more arid conditions to complete the formation.

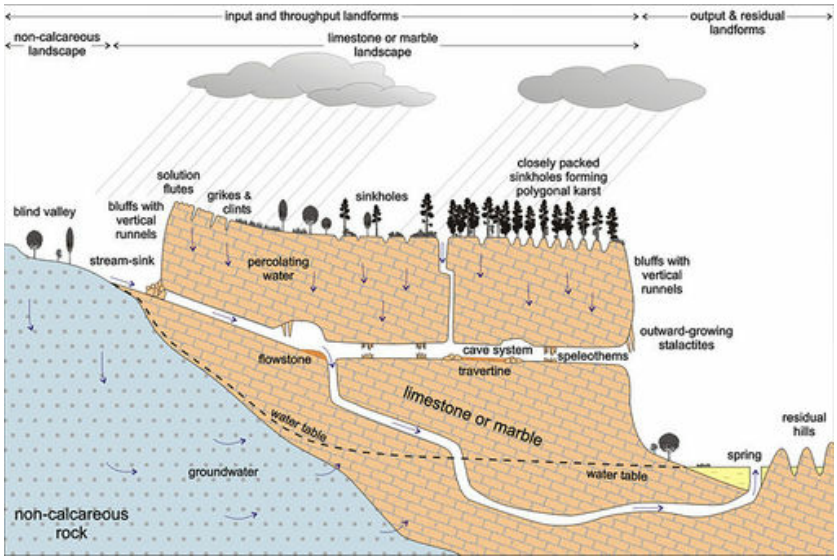
LIMESTONE LANDFORMS

Limestone is one of the most common sedimentary rocks found in the world. Eye-catching features such as caves, sinkholes and spectacular skyline landscapes are often associated with limestone formations. These landforms have developed through the interaction of rocks, water and climate.

Karst landscapes

The word ‘karst’ comes from a German word used to describe the stony limestone landscape. It is the distinctive surface and underground landforms such as caves, fluted rock outcrops and dolines or sinkholes that the term ‘karst’ implies.

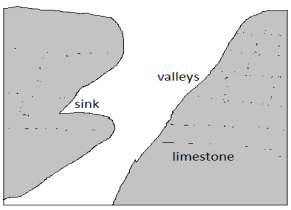
Limestones that are relatively pure and hard with a high percentage of calcium carbonate are the ones that tend to develop the best karst features. Caves are always found in karst environments since they provide the passageways for underground water drainage. Caves often develop stunning features such as stalactites, stalagmites and columns. The formation of these structures is the reverse of the dissolution of the calcium carbonate with acidic rainwater.



Fluted rock outcrops have been formed as a result of the chemical action of rainwater on the limestone. As the rainwater flows over and down the limestone outcrop, it erodes the surface, resulting in the outcrop taking on a grooved or fluted appearance.

A karst landscape's surface is often dotted with bowl-shaped hollows called sinkholes or dolines. They vary in size but are most often up to 100 metres in diameter and tens of metres deep.

Blind valleys

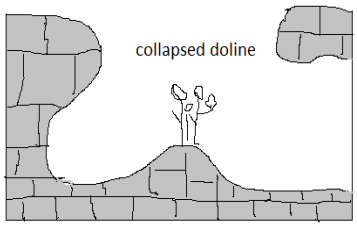


This is a valley closed on the lower end by the rock wall. The valley is caused by the lowering of the river bank by solution weathering around the sink and eventually retreats upstream due to partial underground collapse.

Dolines

It is a shallow depression or hollow with gently sloping sides and generally circular or oval in shape. Dolines occur in large groups and this is mainly due to water percolating underground. The rock is slowly dissected and a small basin is formed and is gradually enlarged.

Collapsed dolines



Unlike dolines, collapsed dolines have steep sides and they are caused by the collapse of part of an underground curve. See diagram below:

Polje

This is a very large, shallow, steep sided depression with a generally flat floor. It can be many km in size. The flat floor is often emphasized by the deposition of terra-Rosa and clay material which may form an impermeable layer which can lead to flooding after heavy rains. A polje may hold temporary/ permanent Lake.

Sinkholes

This is a deep hole with nearly vertical sides leading to an underground cave system. Some result mainly from surface solution. Many are located on the floors of dolines, uvalas and poljes. A sink is when a river disappears underground and reappears downstream (swallow hole).

GEOMORPHOLOGY OF SLOPES

Slopes are an important aspect in geomorphology because they help candidates understand the development of various landforms. This section focusses on slope form and development as well as factors that influence slope development. Processes on slopes are also covered in this section.

Slope Form

Slope form refers to the shape of the land surface. It is what you see when you look at a landscape. Whether a slope is steep or gentle, irregular or smoothly curved, high or low, are features of its form. The form of a slope, that is, the slope of the ground surface, can be describe in terms of profile form and plan form.

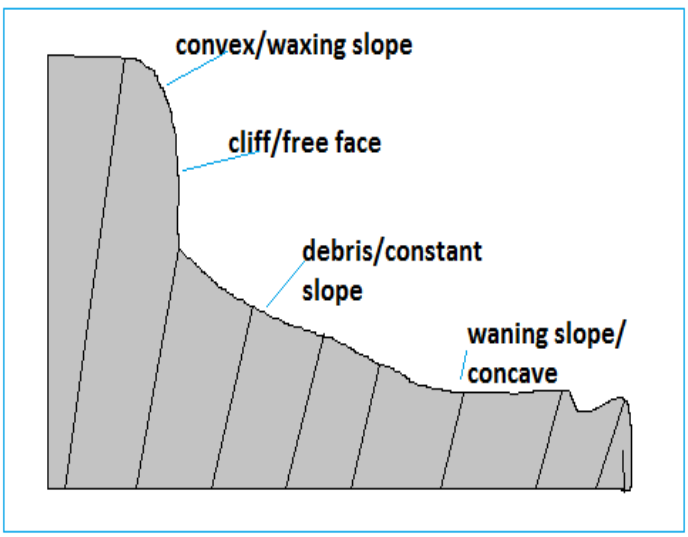
Profile form is a shape when viewed in profile, as if a cross-section were taken at right angles to the hillside.

Plan form is the shape when viewed from above; it is shown on a map by the curvature of contours.

Profile analysis is to divide it into straight and curved parts, called slope units. The straight parts, on which the angle remains approximately constant, are termed rectilinear segments. The curved parts are convex and concave segments. A segment that is steeper than the slope units above and below it is a maximum segment. Above the maximum segment is the convexity and below it the concavity.

Four-unit model

It was proposed by A. Wood in 1943.



The waxing slope or concave slope- is the curve over edge of the horizontal surface of the hilltop. It is also called the convex slope or upper wash slope.

The cliff/free face - A steep slope or part of a slope formed of bare rock.

The debris/constant slope- is a slope with a uniform angle that did not alter as the slope developed through time. Many constant slopes only have a very thin cover of rock waste. It usually extends upward to the rock-cut slope of the free face.

Waning/concave slope- stretches to the valley floor with diminishing angle and is characterized with fine materials. It is also known as pediment, valley- floor

basement or lower wash slope.

Factors affecting the Development of slopes

i) *The influence of rock structure and lithology on slopes*

- Lithology influences profile form and angle. The strength, stability and permeability of a rock are important factors in determining slope form, e.g. convexities form the greater part of profiles developed on sandstones, about half on Limestones and less than half on shales. Maximum slope angles also very with lithology, (e.g. max. slope angle on limestone is usually about 20º, shales 9 º, and on clays 5.5 º)

- The nature of the regolith which is formed is also important, e.g. surface wash as a slope forming process depends on the permeability of the regolith. Surface wash is more effective on less permeable regolith such as clay.

- The presence of joints, cracks and bedding planes can allow increased water content and so lead to sliding

ii) *The influence of climate on slopes*

- It affects surface processes directly and indirectly. For example, it determines the significance of weathering processes such as frost shattering or surface run-off.

iii) *The influence of vegetation on slopes*

- The main effect of vegetation is the protection it gives the soil from surface wash and rain splash.

- Other effects are: the action of roots in holding the regolith on the slope, the contribution to chemical weathering by the products of organic acids and the supply of organic matter which improves soil structure.

iv) *Human influence*

- Deforestation increases the rate of slope movement.

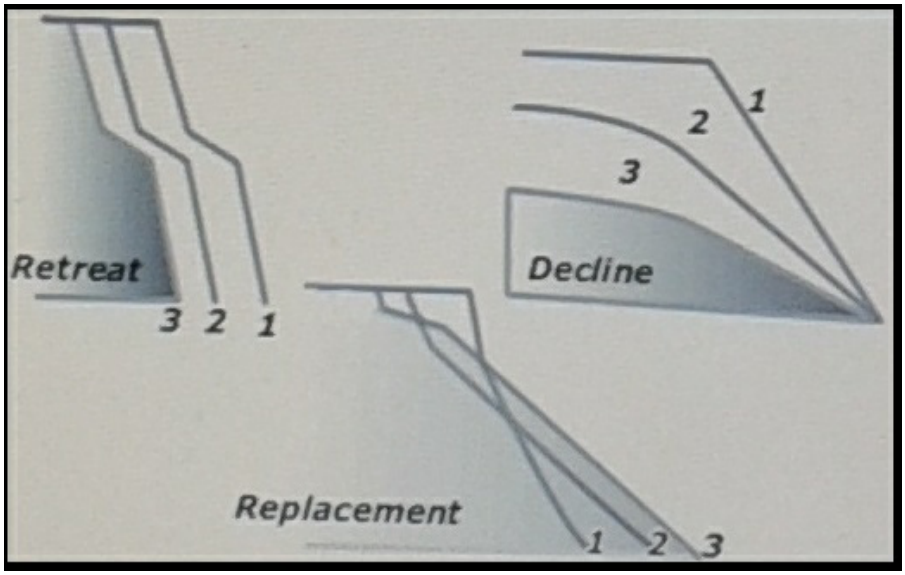
- Building road or quarrying at the foot of slopes upsets the equilibrium.

- The shaking action of heavy traffic.

- The grazing of animals and ploughing loosen soil and remove protective vegetation cover.

Slope Evolution theories

Evolution is the change in slope form with time, as brought about by the action of processes. Three models of slope evolution have been proposed: these are called slope decline, slope replacement, and parallel retreat.



Slope decline(W.M. Davis, 1899)

- Theory based on slopes in what was to Davis a normal climate, NW Europe and NE USA.

- Slope decline is common in many humid temperate regions.

- Davis' theory is based on the assumption that steepest slopes at beginning of the process experience a progressively decreasing angle in time to give a convex upper slope and a concave lower slope.

The movement of rock waste is seen as one stage between weathering on one hand and transportation by rivers on the other. The forms of slopes change as the cycle of erosion advances. When slopes are first developed they are steep and covered with coarse material. Later in the cycle the graded slopes are gentler and are covered with a thicker layer of finer material. The slope decline is caused by the fact that the downwash of soil from convex upper slopes is faster than its removal from the slope base.

Slope replacement(W. Penck, 1924)

- The theory of slope replacement is particularly applicable to explaining the slope development of cliffs in subtropical semi-humid climatic areas.

- The maximum angle decreases as the gentler lower slopes erode back to replace the steeper ones giving a concave central portion to the slope.

- This theory assumes that the surface of the slope is weathered evenly and crumbles with the fragments (scree) falling tothe base. Thus maximum angle of the slope decrease and is replaced by a gentler slope.

Slope retreat (or Parallel retreat) (L.C. King, 1948, 1957)

- The theory of slope retreat is particularly applicable to explaining the slope development in semi-arid areas.

- The maximum angle remains constant as do all slope facets apart from the lower one which increases in concavity.

- Each of the upper parts of the slope retreats by the same amount and maintains the same angle. Thus the convexity, free face and debris slope all retain the same length, both absolute and relative to each other during retreat. The pediment

extends in length and becomes slightly gentler in angle.

SLOPE PROCESS

Slope process refers to the active agents which bring about changes in landforms, for example the impact of falling raindrops or running water. The rates at which slope processes act can be measured.

MASS MOVEMENT

Mass movement – The bulk movement of weathered and broken rockmaterials down slopes under the influence of gravity. OR the down-slope movement of material, whether it be bedrock, regolith, or a mixture of these, is commonly referred to as a ***landslide***.

Factors affecting mass movements

Gravity – the force of gravity provides the energy that causesmaterial to move downhill. Gravity is always acting!!

Internal cohesion (strength) – the characteristic property of arock or soil that measures how well it resists being deformed orbroken by forces such as gravity. For example bedding planes in sedimentary rocks (especially thoseinvolving clay or other "weak layers") nearly parallelto the slope are very susceptible to sliding, while uncemented dry sand and coarser fragments have verylittle internal cohesion and assume an "angle of repose"which is the maximal slope at which material will remainstable.Clays in the sediment promote higher internal cohesionin dry unconsolidated material, but they allow for easier downhill slippage when wet.

Water- Clay becomes plastic and weak when it absorbs water. Wet clays not only act as lubricants for mass movements, but tendto flow out laterally from beneath burdens, thus causingsubsidence and slumping.

Water in fractures and pores generally reduces the strengthof rocks and clay-bearing soils. It promotes mass movementbecause it is under pressure, which tends to push apartindividual grains and open joints and bedding planes.

Steepness of slopes- the steeper the land surface (i.e., the slope) the larger thecomponent of gravity acting parallel with the slope. This increases the tendency of material to move downhill.

Nature of vegetation - Plants are able to protect soil and regolith against erosion by binding grains together with root systems.

External factors - Earthquakes – vibrations can trigger failure in weakenedrock or soil masses increasing the rate of mass movement while man-madeexcavations can remove material at the base of a slope, promoting sudden slope failure and mass movement.

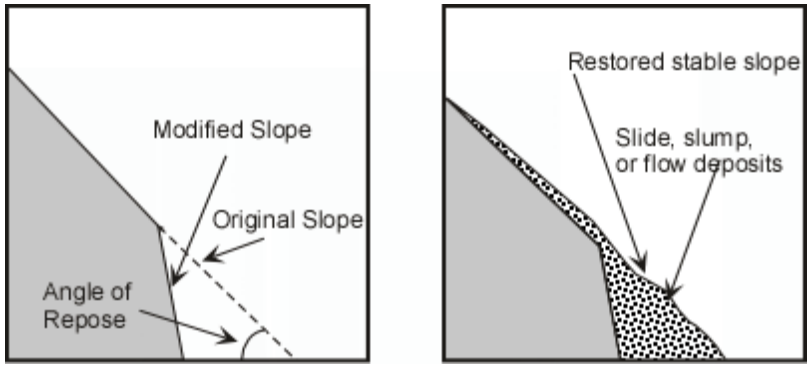
Triggering Events

A mass movement can occur any time a slope becomes unstable. Sometimes, as in the case of creep or solifluction, the slope is unstable all of the time and the process is continuous. But other times, triggering events can occur that cause a sudden instability to occur. Here we discuss major triggering events, but it should be noted

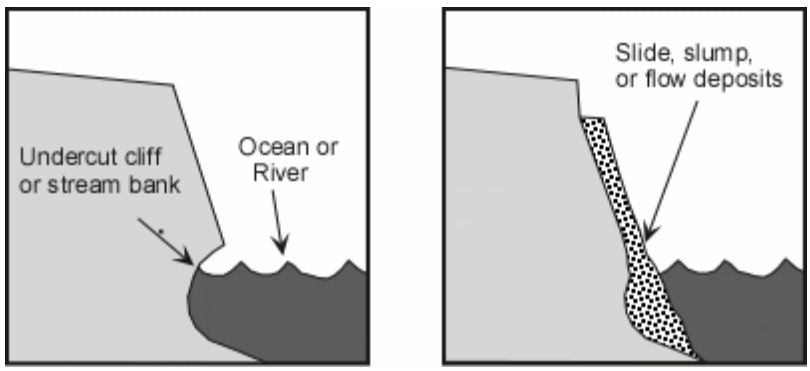
that it if a slope is very close to instability, only a minor event may be necessary to cause a failure and disaster. This may be something as simple as an ant removing the single grain of sand that holds the slope in place.

- Shocks and vibrations - A sudden shock, such as an earthquake may trigger slope instability. Minor shocks like heavy trucks rambling down the road, trees blowing in the wind, or human made explosions can also trigger mass movement events.

- Slope Modification - Modification of a slope either by humans or by natural causes can result in changing the slope angle so that it is no longer at the angle of repose. A mass movement can then restore the slope to its angle of repose.



- Undercutting - streams eroding their banks or surf action along a coast can undercut a slope making it unstable.



- Changes in Hydrologic Characteristics - heavy rains can saturate regolith reducing grain to grain contact and reducing the angle of repose, thus triggering a mass movement. Heavy rains can also saturate rock and increase its weight. Changes in the groundwater system can increase or decrease fluid pressure in rock and also trigger mass movements.

- Changes in slope strength - Weathering creates weaker material, and thus leads to slope failure. Vegetation holds soil in place and slows the influx of water. Trees put down roots that hold the ground together and strengthen the slope. Removal of tress and vegetation either by humans or by a forest fire, often results in slope failures in the next rainy season.

- Volcanic Eruptions - produce shocks like explosions and earthquakes. They

can also cause snow to melt or discharges from crater lakes, rapidly releasing large amounts of water that can be mixed with regolith to reduce grain to grain contact and result in debris flows, mudflows, and landslides.

MECHANISMS OF MASS MOVEMENTS

A. Falling – blocks fall down steep slopes or cliffs

B. Sliding – downward slip of blocks of rock

C. Flow – unconsolidated materials like soils, clay and weatheredshale on slopes can undergo slow plastic flow

D. Frost heave – repeated freezing and thawing or swelling andshrinking of clay results in very slow downward movements of surfacematerials. If conditions are right, water that soaks into the groundduring winter months, freezes and permits ice to accumulate in thezone of freezing as water is added from the atmosphere above and isdrawn upward from the unfrozen ground below. In time masses of iceare built up, and the soil above them is heaved upward. During theprocess of frost heaving, material moves up with each interval offreezing (expansion) and down with each interval of thawing(contraction). Therefore, material moves downslope with eachfreeze-thaw cycle.

CLASSIFICATION OF MASS MOVEMENTS

Mass movements can be classified on the basis of how fast thematerial moves.

Slow Movements- Slow, inexorable downslope movement of material under theinfluence of gravity. Examples are creep and frost heave

Moderate Movements- these are moderate movements that occurs on slopes and examples include earthflow, mudflow, and debris flow.

Rapid Movements- is where material moves very fast on slopes. Examples are:

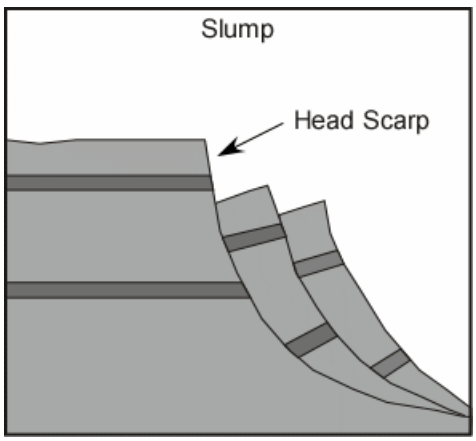
MASS MOVEMENT PROCESSES

1. Slope Failures - a sudden failure of the slope resulting in transport of debris downhill by sliding, rolling, falling, or slumping.

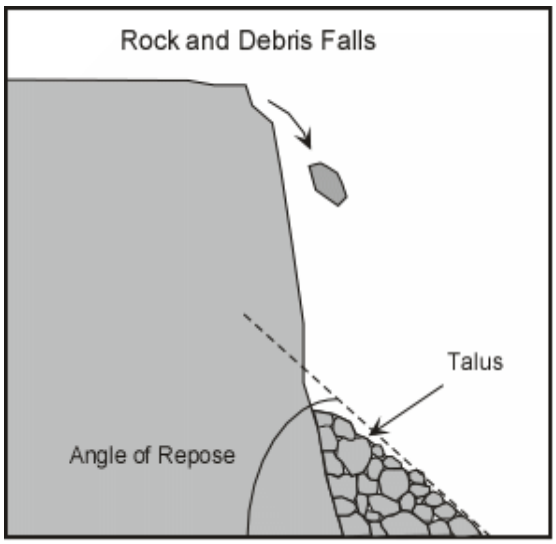
2. ***Sediment Flows*** - material flows downhill mixed with water or air.

Slope Failures

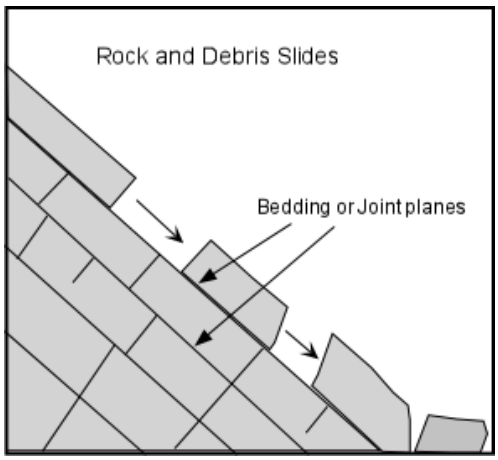
- ***Slumps*** - types of slides wherein downward rotation of rock or regolith occurs along a curved surface. The upper surface of each slump block remains relatively undisturbed, as do the individual blocks. Slumps leave arcuate scars or depressions on the hill slope. Heavy rains or earthquakes usually trigger slumps.



- ***Rock falls and Debris falls*** - Rock falls occur when a piece of rock on a steep slope becomes dislodged and falls down the slope. Debris falls are similar, except they involve a mixture of soil, regolith, and rocks. A rock fall may be a single rock, or a mass of rocks, and the falling rocks can dislodge other rocks as they collide with the cliff. At the base of most cliffs is an accumulation of fallen material termed ***talus***. The slope of the talus is controlled by the angle of repose for the size of the material. Since talus results from the accumulation of large rocks or masses of debris the angle of repose is usually greater than it would be for sand.



- ***Rock Slides and Debris Slides*** - Rock slides and debris slides result when rocks or debris slide down a pre-existing surface, such as a bedding plane or joint surface. Piles of talus are common at the base of a rock slide or debris slide.Factors that frequently contribute to rock slides or avalanches are steep mountain sides, bedding planes parallel to the slope, faults that break bedding planes, weak layers (wet clays or coal, for example)which can undergoslow plastic deformation under the weight ofrock upslope and Earthquakes



Sediment Flows

Sediment flows occur when sufficient force is applied to rocks and regolith that they begin to flow down slope. A sediment flow is a mixture of rock, regolith with some water. They can be broken into two types depending on the amount of water present.

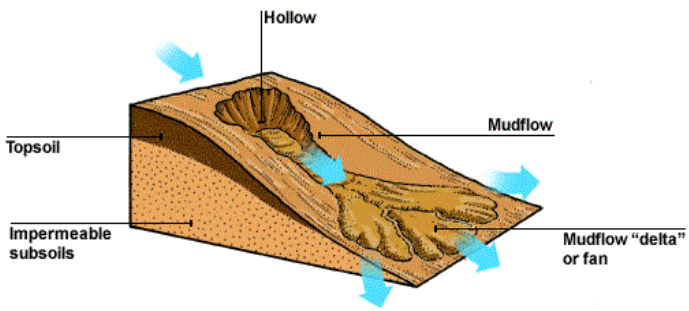
1. ***Slurry Flows***- are sediment flows that contain between about 20 and 40%

water. As the water content increases above about 40% slurry flows grade into streams.

2. ***Granular Flows*** - are sediment flows that contain between 20 and 0% water. Note that granular flows are possible with little or no water. Fluid-like behaviour is given these flows by mixing with air.

Each of these classes of sediment flows can be further subdivided on the basis of the velocity at which flowage occurs.

- ***Slurry Flows (high amounts of water)***
  - ***Solifluction*** - flowage at rates measured on the order of centimetres per year of regolith containing water. Solifluction produces distinctive lobes on hill slopes. These occur in areas where the soil remains frozen and is then is thawed for a short time to become saturated with water.
  - ***Debris Flows*** - similar to mudflows except that they contain many large fragments of rocks and trees, all carried in the moving mixture of sand, silt, clay, and water. These occur at higher velocities than solifluction, and often result from heavy rains causing saturation of the soil and regolith with water. They sometimes start with slumps and then flow downhill forming lobes with an irregular surface consisting of ridges and furrows.
  - ***Mudflows*** - a well-mixed mass of rock, soil and water that flows downslope. It has a consistency like concrete and supersaturated with water. Tend to travel in stream-like masses within valleys and canyons. Their formation is favoured by sudden abundance of water, lack of vegetation, and abundance of loose regolith or unconsolidated sediment. Often these conditions are found in arid regions that are subjected to periodic torrential rains. One such region is California, where periodic brush fires leave the ground without protection against the next heavy rainfall.



Thus, after a heavy rain streams can turn into mudflows as they pick up more and more loose sediment. Mudflows can travel for long distances over gently sloping stream beds. Because of their high velocity and long distance of travel they are

potentially very dangerous. Mudflows on volcanoes are called ***lahars.***

- ***Granular Flows (low amounts of water)***
  - ***Creep-*** the very slow, usually continuous movement of regolith down slope. Creep occurs on almost all slopes, but the rates vary. Evidence for creep is often seen in bent trees, offsets in roads and fences, and inclined utility poles (see figure 16.2c in your text).
  - ***Earthflows -*** sluggish, rather erratic flow ofclayey or silty regolith down relatively gentle slopes. Water is present, but usually not at saturation. Sometimes recognizable by a curved scarp (portion of slip surface exposed) that develops at the breakaway line on the slopeand by the crescent-shaped bulges at the "toe" of the flow.
  - ***Grain Flows -*** usually form in relatively dry material, such as a sand dune, on a steep slope. A small disturbance sends the dry unconsolidated grains moving rapidly down slope.
  - ***Debris Avalanches -*** These are very high velocity flows of large volume mixtures of rock and regolith that result from complete collapse of a mountainous slope. They move down slope and then can travel for considerable distances along relatively gentle slopes. They are often triggered by earthquakes and volcanic eruptions. Snow avalanches are similar, but usually involve only snow.

Mass-Movements in Cold Climates

Mass movements in cold climates is governed by the fact that water is frozen as ice during long periods of the year. Ice, although it is solid, does have the ability to flow, and freezing and thawing cycles can also contribute to movement.

ARID AND SEMI-ARID ENVIRONMENTS

DEFINITION OF TERMS

Desert- *the term desert is used to express 'aridity' which means moisture deficit. It originated from a Latin word* ***"desertus"*** *which means 'abandoned.' Desert areas are moisture stressed and as a result they lack biodiversity (flora and fauna). Waugh D described a desert as an area that receive an annual rainfall total below 250mm. High evapotranspiration rates also contributes to moisture deficit in deserts.*

Aridity- *refers to the general lack of moisture in an area or the expression of moisture deficiency resulting from a permanent absence of rainfall (little rainfall). Aridity is also explained as the degree of dryness of an area which can be categorized into 3 groups:*

(i) Semi-arid: are areas with 2 distinct seasons (summer and winter), receiving summer rainfall, which is, however, inadequate to support biodiversity (rainfall is above 250mm but less than 400mm).

(ii) Arid areas- these are characterised by spasmodic, sporadic or infrequent storms. The annual rainfall total does not exceed 250mm.

(iii) Extreme arid areas- are areas which are extremely dry with no rainfall throughout the year. If it falls, it doesn't exceed 24mm per year hence these areas lack flora and fauna.

Deserts can further be categorized into 2 i.e. hot deserts and cold deserts.

(i) Hot deserts are characterised by very high day temperatures and very low night temperatures. Such deserts have maximum temperatures of about 40^0C and a very large diurnal temperature range.

Hot Deserts of the World

Name and *Location*	**Size**	**Physical Features**	**Plants & Animals**
Australian (Great Sandy, Victoria, Simpson, Gibson, and Sturt) *Australia*	2,300,000km^2 (1/3 of Australia)	Great Sandy, Victoria, and Simpson are sandy; Gibson and Sturt are stony.	acacia, casuarinas tree, eucalyptus, saltbush, blue-tongued lizard, dingo, fat-tailed mouse, kangaroo, marsupial mole, rabbit-eared bandicoot, sand goanna,
Kalahari *South-western Africa*	520,000 km^2	Covered by sand dunes and gravel plains.	acacia, aloe gazelle, gerbil, ground squirrel, hyena, jackal, sand grouse, springbok
Sahara		Covered by mountains, rocky areas, gravel plains,	acacia, grasses, tamarisks

Northern Africa	9,100,000km^2	salt flats, and huge areas of dunes. Areas in the central sometimes get no rain for years at a time.	addax antelope, gazelle, fennec fox, horned viper, jackal, jerboa, sand grouse, spiny lizard

Hot desert climate has the following characteristics:

- high day temperatures due to lack of cloud cover
- very low night temperatures due to nocturnal radiation or free heat loss (large diurnal temperature range)
- low rainfall not exceeding 300mm due to permanent high pressure systems
- dust storms due to strong winds and lack of vegetation cover
- sudden, short-lived erratic storms with high intensity due to localized heating (spasmodic storms)

Most hot deserts are found on the western sides of the continents due to the effect of cold ocean currents that sweeps the areas. See details on the causes of deserts.

(ii) Cold deserts are characterised by very low temperatures and permanent frost for example the Siberian desert. See other examples below:

Cold Deserts of the World			
Atacama *Coasts of Peru and Chile*	54,000 mi^2 140,000 km^2	Covered by sand dunes and pebbles. One of the driest areas on earth.	bunchgrass, cardon cactus, tamaruga trees lizards, llama, Peruvian fox, nesting area for many seabirds
Gobi *Northern China and Southern Mongolia*	450,000 mi^2 1,200,000 km^2	Covered by sandy soil and areas of small stones called "gobi."	camel's thorn, grasses Bactrian bamel, gazelle, gerbil, jerboa, lizards, onager, wolf
Namib *Coasts of South-western Africa*	52,000 mi^2 135,000 km^2	Covered by sand dunes along the coast and gravel farther inland.	aloe, bunchgrass, lichens, welwitschia darkling beetle, fringe-toed lizard, golden mole, jackal, sidewinder, viper

Deserts can also be further categorised according to their location, i.e. maritime deserts and continental deserts. ***Maritime deserts*** are those deserts which are adjacent to water

bodies (close to coastal areas) for example the Namib Desert which is adjacent to Atlantic Ocean or the Atacama Desert adjacent to Pacific Ocean. On the other hand, ***continental deserts*** are those found in the interior of continents e.g. the Sahara, Australian, Gobi, and Arizona Deserts.

CAUSES OF DESERTS

Rainshadow effect-*Moisture-laden air encounters a mountain mass and is moved upward. The ascending onshore winds are cooled adiabatically and releases moisture on the windward side of the range. Once over the summit, the air descends on the leeward side of the range, warming adiabatically as it does so, and hence reducing rainfall formation resulting in desert formation. This is called the rainshadow effect. In summary, the rainshadow effect shows that adiabatic cooling occurs on the windward side when onshore winds are forced to rise by mountain ranges, producing rainfall here. On the other hand adiabatic warming occurs as the air descends on the leeward side, preventing rainfall formation. This creates deserts e.g. the Atacama Desert in South West America which is caused by the presence of Andes mountain range.*

Cold ocean currents- *The southwestern coasts of Africa and South America are swept by cold currents upwelling from the ocean floor. These currents cool the onshore winds that passes over them by advection, reducing the water-holding capacity of the air. Cold air holds less moisture or have a relatively small moisture-bearing capacity than warm air.As a result such areas receive precipitation in the form of mist and fog hence arid conditions would prevail. The Namib and Atacama Desert have formed because of these cold currents.*

NB- This factor explain why most deserts are found on the western sides of continents.

Atmospheric high pressure zones – *most deserts are located around 30^0 North and South of the equator; i.e. along the Tropic of Cancer in the North and Tropic of Capricorn in the southern hemisphere. These two latitudes are called Horse latitudes or subtropical highs. They are characterised by high pressure caused by descending air. Subsiding air warms up and reduces rainfall formation because warm air have more evaporative power hence permanent dry conditions prevail in high pressure areas. The Sahara desert was formed as a result of this effect.*

Continentality or *Distance from oceans* – *this factor explain the location of deserts in the interior of large continents like Africa. Areas lying deep within a continent may become desert simply as a result of being located far from the ocean, from which most atmospheric moisture is drawn. The moisture is precipitated before it can reach these interior areas. The Gobi Desert in China and the Kalahari Desert in Botswana are good example.*

Types of deserts

Sandy desert (Erg) – vast areas of sea sand with miles of sand dunes and ripples. The Namib Desert is a good example. Roads are difficult to construct because of migratory sand dunes. The terrain is too harsh for wildlife, plants find it hard to get rooted and

animals get easily exhausted in the soft sand.

Stony desert (Reg) – is a bare flat, stony surface consisting of layers of packed gravel; formed by wind erosion which removes sand. Since the ground is solid and stable (unlike sandy desert) bushes, tufts of grass and some animals may be present.The Kalahari, lower Atacama and Sahara deserts are good examples.

Rocky desert Hamada) - is that where sand and stone were washed or blown away. This is usually associated with very hilly or mountainous terrain exposing very hard rocky material. An example would be the upper Atacama Desert or parts of the US states of Arizona and Utah. Some adapted wildlife also exists.

Mountain Deserts- are scattered ranges of dissected hills or mountains separated by dry, flat basins. Most of the infrequent rainfall occurs on high ground and runs off rapidly in the form of flash floods. These floodwaters dissect mountains and hills. *See also badlands*.

DESERTIFICATION

Desertification refers to the spreading of desert into areas lying on the edges of the present deserts (marginal areas) or the continuous encroachment of desert like conditions into non-desert areas and areas bordering deserts. In other words desertification is a process whereby non-desert areas are being turned into deserts due to anthropogenic (human) factors and natural factors. This problem is particularly significant in those parts of Africa close to the Sahara desert known as the Sahel region.

Desertification as a process can be classified into 3 groups:

- Slight desertification: here the process of desertification is not yet evident or visible but it is slowly taking place. There is no deterioration in plant cover yet.
- Moderate desertification: here the process of desertification is slightly becoming visible and there is an increase in undesirable species such as shrubs. There is accelerated wind and water erosion as well as salinization of the soil. Plant cover begins to deteriorate.
- Severe desertification: here evidence of desertification is quite visible.

Causes of desertification:

Desertification is caused primarily by human activities and climatic variations.

Climate change- is a natural cause of desertification. Climate change increases the intensity of drought and floods, yet rainfall become erratic as a result of climate change. This substantially increases desertification in the Sahel region.

Global warming- is also another natural cause of desertification. Global warming refers to an increase in atmospheric temperature. However, global warming is classified under human activities because it is

largely caused by humans.

Drought-(natural cause). Drought means that crops and natural vegetation will dry out. Lack of a protective vegetative cover increase erosion and land degradation and resultantly increase desertification.

Population pressure-has led to overgrazing by animals, over-cultivation of poor soils and the cutting down of trees and shrubs for use as fuel. The loss of the protectionleads to the further removal of the soil cover and the consequent spread of the desert.

Overgrazing- Overgrazing is one of the greatest causes of desertification. Land is left bare and prone to degradation. Overgrazing is caused by overstocking of animals, exceeding the carrying capacity of the land.

Cultivation of marginal lands- Marginal lands are dry or arid areas which are not suitable for profitable cop production (arable farming), which have poor soils and other undesirable characteristics. Because of rapid population growth, marginal areas are now used for agriculture; however with dire consequences one of which is desertification.

Deforestation-Destruction of plants in dry regions is causing desertification to occur. People are cutting down trees to use them as a source of fuel.

Irrigation- in Arid Regions irrigation leads to the accumulation of salts in the A horizon.The accumulation of salts is called Salinization. This process leaves a hardened crust which does not support plant life. As a result, land degradation occurs followed by the widespread expansion of deserts.

The Effects of Desertification

Soil becomes less usable-The soil can be blown away by wind or washed away by rain, removing important plant nutrients. Salts can build up in the soil which makes it harder for plant growth.
Vegetation is damaged- vegetation is damaged by erosion. Also, when overgrazing occurs, plant species may be lost. This also lead to excessive loss of livestock

Food Loss- The soil is not suited for growing food; therefore the amount of food being made will decline. If the population is growing, this will cause economic problems and starvation.

Shortage of water for domestic and industrial uses

How to prevent desertification and its devastating impacts

Desertification can be prevented or, at least, slowed down in a number of ways. These include:

- *Government can introduce financial aid to support affected areas for example areas affected by crop failure. The government can also introduce drought relief in the form of food aid. The government can also introduce community food aid through programs such as food for work.*
- *Signing of international agreements to fight desertification for example the Kyoto Protocol in Japan or the Montreal protocol in Canada. By participating in these international agreements, the government will be committed to meet set goals and objectives that will go a long way in preventing desertification.*
- *Introduction of early forecast and prediction of droughts inorder to improve hazard awareness and preparedness.*
- *Introduction of irrigation scheme in areas of low rainfall inorder to improve food production for example the Mushandike irrigation project in Masvingo; Zimbabwe.*
- *Dam construction to improve water holding capacities and rainfall for example the Tokwe-Mukosi*

Dam in Masvingo.

- *Reduction in the number of grazing animals or destocking of animals*
- *Planting of trees through afforestation and reforestation programmes and prevention of deforestation through the use of energy substitutes, e.g. use of biogas, tsotso stove which does not require big logs, solar power e.t.c. In Zimbabwe, the government introduced a national tree planting day to promote re-vegetation. Deforestation can further be prevented through rural electrification programmes*
- *Education and training of people on proper farming methods*
- *Enforcement of environmental protection laws to reduce deforestation and* cultivation of marginal lands

Case Study: The Sahel Region

The Sahel is the semi-arid transition region between the Sahara desert and the wetter regions of equatorial Africa. It has high variability of rainfall, and the land consists of stabilized ancient sand seas. It is one of the poorest and most environmentally degraded areas on earth.

In the Sahel Desert, desertification is becoming a huge problem. Around the 1950's, people settled into the Sahel region, in areas where there was water. This resulted in overgrazing, which is one of the greatest causes of desertification. A lot of the topsoil was washed away, and all that was left were rocks. Silt turned hard when it was hit by rain. Therefore, plants were not able to grow because the roots could not penetrate this hard layer. Now this region has turned to desert and it continues to expand. Another reason desertification is occurring in the Sahel region is because people are using the slashing and burning method to clear land. This degrades the quality of soil just like

Evaluation of measures stated above: successes and failures

- Shortage of electricity and frequent power cuts increase the need for firewood in both rural and urban areas meaning that deforestation remains a huge problem. In addition, the rate of rural electrification is slow due to lack of funds, such that most rural areas of Zimbabwe (for example) are still using wood fuel for cooking and warming. Most rural people in Africa are poor hence they cannot afford huge electricity bills and this means that they are forced to continue using fuelwood which is cheaper for them.
- Cultural attitudes towards the measures- some people resist proposed measures to reduce desertification simply by sticking to their cultural beliefs, for example on the destocking of animals where on cultural basis people find comfort in quantity than quality. This means that they continue to keep large herds.
- Refusal on political grounds- some of the proposed measures are simply rejected because of superiority of some people on political grounds.

- Lack of better options due to population pressure on resources. In most Less Economically Developed Countries like Zimbabwe, the rate of population growth is rapid such that people are forced to continue cutting down trees to open up new areas for agriculture and settlements. This happens due to population pressure on resources.
- Ignorance of people
- Lack of capital
- Drought which reduce vegetation cover.
- NB- some of the measures were however successful for example the enforcement of environmental protection laws by EMA in Zimbabwe.

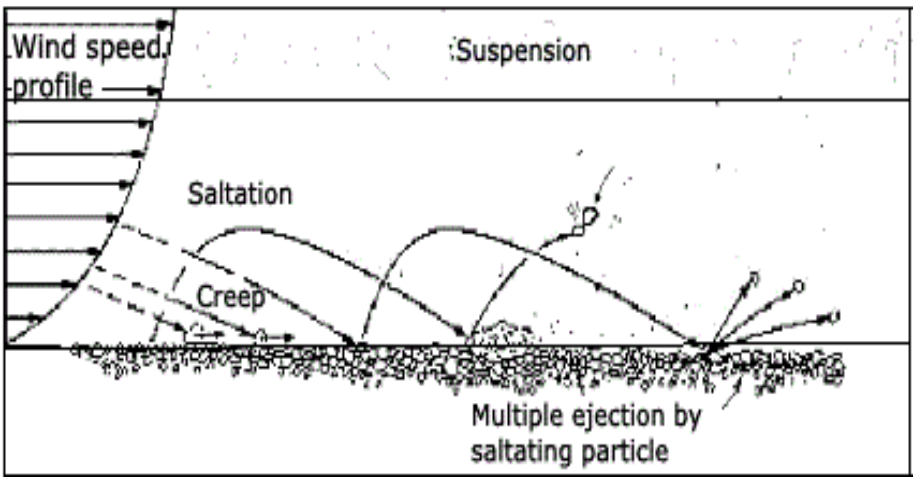
WIND ACTION IN DESERTS

NB- Wind plays a vital role in landform development in deserts. Desert landforms are either produced by wind erosion or deposition. Wind action is particularly significant in landform development because deserts lack moisture and vegetation to bind the soil and prevent the influence of wind. In addition, the presence of sandy, loose soils also aid wind action in deserts. Deserts frequently experience very strong winds which means that the action of wind in shaping desert landscape is more important than the action of water.

Wind transportation

Question- describe ways in which wind transport its load in arid areas. [9]

Wind transportation is largely determined by wind velocity, nature of surface material and the size of materials. There are three processes of wind transport, i.e. suspension, saltation and surface creep.



Suspension- *is whereby the sheer force of the wind picks up the materials such as fine sand, silt and clay particles(less than 0.5mm in diameter); and transport them in raised or suspended position for considerable distances. The material remain suspended above the ground as long as the wind still has the capacity to raise the*

material. Suspended material can be raised up to 100m above the ground depending on the strength of the wind.

NB- Suspension is very common in the Sahara desert where it causes dust storms comprising red clay that reduces visibility to about 10km.

Saltation- *involves the transportation of relatively larger and medium sized particles in a hoping and bouncing manner in the direction of wind or the transportation of rock particles and sand in a series of jumps/leaps. It involves the jumping up and down of particles as they respond to the strength of the wind. Saltation occurs when the velocity of wind is greater than threshold velocity (speed required to initiate grain movement). When the threshold velocity is exceeded by wind speed, a particle is lifted and saltation occurs.*

Traction or surface creep or drift- *involves the rolling, dragging and sliding of large particles (above 2.5mm in diameter e.g. pebbles) as they are transported by violent and strong wind. The load in this case resist uplift because the sheer force of wind can only exceed frictional drag.*

Aeolian erosion or wind erosion in deserts

Wind erosion depends largely on the erosive strength of the wind although surface characteristics, moisture content, and vegetation cover are also important factors. Wind can erode by ***deflation, attrition*** and ***abrasion***.

Deflation is the lowering of the land surface due to removal of fine-grained particles by the wind. This is erosion which involves the removal of loose weathered material by wind. Deflation concentrates on the fine-grained particles at the surface, eventually resulting in a surface composed only of the coarser grained fragments that cannot be transported by the wind. Such a surface is called ***desert pavement***.

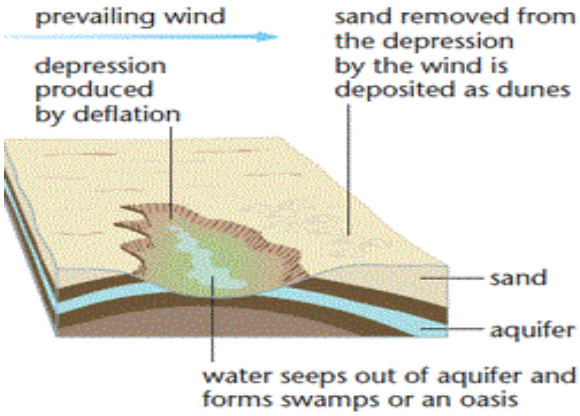
If deflation occurs in areas where chemical weathering weakens the soil forming deep regolith, the regolith is going to be blown away creating very steep depressions such as the Zemzem in Libya and the Qattara Depression in Egypt. These depressions are called deflation hollows and they can reach a depth of more than 100m. Sometimes deflation persist until the water table is reached and exposed as an oasis.

Abrasion – this is sand blasting process caused by transported sand and rock fragments. Here the impact of saltation particles wears away rock surfaces creating spectacular desert features like rock pedestals yardangs and zeugens. ***Rock pedestals, yardangs and zeugens*** are erosion landforms produced by selective abrasion whereby erosion targets the weaker rocks.Wind abrasion is greatest near the ground (1m).

Erosion Landforms

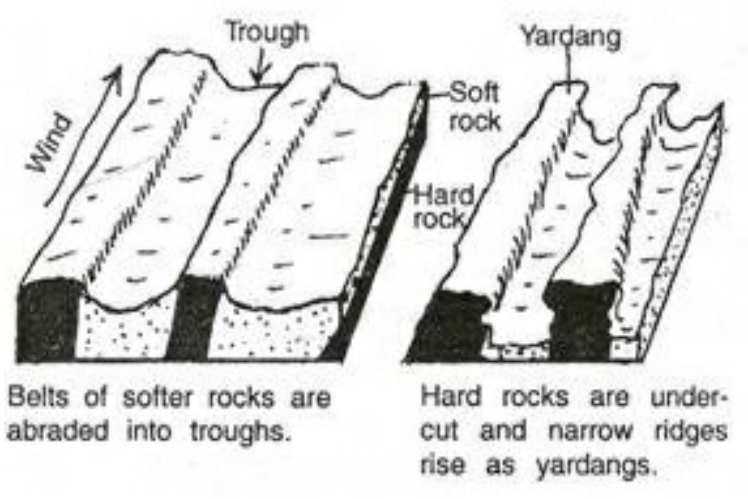
- ***Deflation hollows and desert pavements***- Wind deflation produces

deflation hollows and desert pavements.


prevailing wind
depression produced by deflation
sand removed from the depression by the wind is deposited as dunes
sand
aquifer
water seeps out of aquifer and forms swamps or an oasis

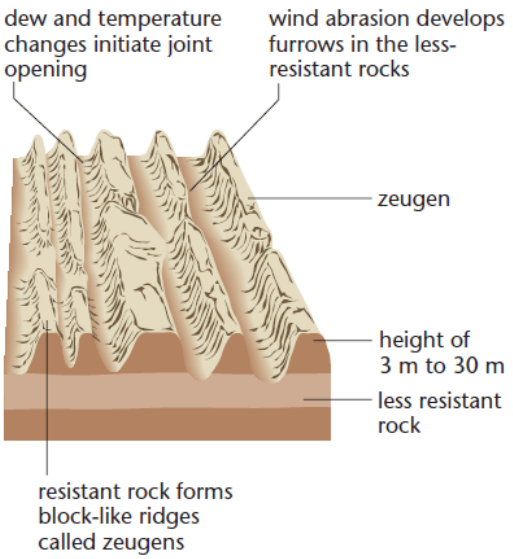
Deflation hollows are depressions formed due to the removal of fine-grained particles by the wind. If wind deflation continues underground water maybe exposed and an ***oasis*** is formed. Deflation hollows also act as channels for water flows in times of flash floods.

❖ ***Yardangs-*** these are formed by sand blasting or wind abrasion on rocks that have vertical bands of hard and soft rock. The alternate layers of hard and soft rocks lie parallel to the direction of prevailing winds such that the softer layer is eroded faster than the hard rock. Selective wind abrasion here, lowers the soft part forming the grooves and if wind abrasion remain concentrated on the weaker rock, the grooves are lowered forming a ridge and farrow landscape.



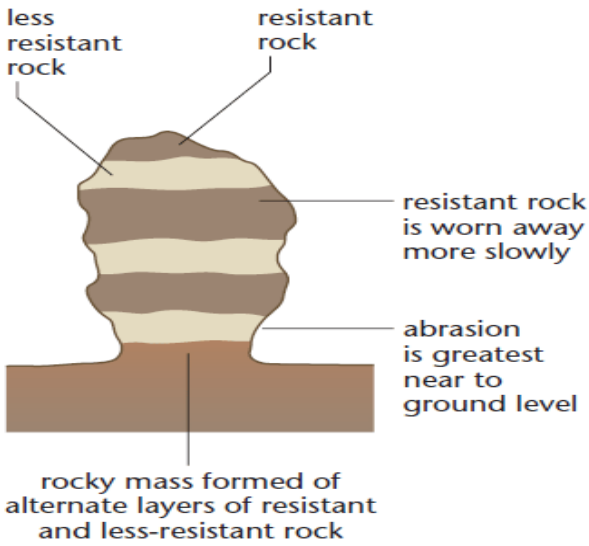
The ridges are the yardangs. Yardangs vary in size and they could be ridges of just a few cm to tens of meters to several kilometres.

❖ ***Zeugens-*** these are tubular masses of rocks formed by wind abrasion in areas that have heterogeneous layers of rocks lying horizontal but across prevailing winds. In this case the weaker rock will be overlain by a harder rock as shown below. The softer rock is exposed to wind abrasion by weathering and faulting and one exposed the weaker rock is lowered (until the more resistant rock below is reached) to form ridges and farrows. The tabular -shaped ridges formed are called the zeugens.


dew and temperature changes initiate joint opening
wind abrasion develops furrows in the less-resistant rocks
zeugen
height of 3 m to 30 m
less resistant rock
resistant rock forms block-like ridges called zeugens

Unlike yardangs zeugens form in rocks that have horizontal bands of hard and soft rock. The ridges are called zeugens which may be as high as 100 feet. Ultimately they are undercut and can gradually collapse.

NB- zeugens and yardangs are similar in that both are ridge and farrow landscapes and they both have alternate layers of hard and soft rocks. However zeugens differ from yardangs in that they have horizontal bands of hard and soft rocks and that zeugens eventually collapse due to undercutting.


less resistant rock
resistant rock
resistant rock is worn away more slowly
abrasion is greatest near to ground level
rocky mass formed of alternate layers of resistant and less-resistant rock

Rock pedestals- these are massive mushroom-shaped rock features which are formed as a result of sand blasting by wind. They have a wide part and a narrow 'stalk', just like a mushroom. They are formed from exposed, isolated rocks with horizontal bands of hard and soft rock. Wind abrasion erodes the soft rock at a faster rate than the hard one. See diagram below

Since wind abrasion is greatest near the ground surface (up to 1m) a very thin stalk is produced forming a mushroom shaped feature in the process.

Wind depositional features

Wind can deposit sediment when its velocity (strength) decreases to the point where the particles can no longer be transported. This can happen when topographic barriers slow the wind velocity on the downwind side of the barrier. Features produced by wind deposition include sand dunes, ripples and loess deposits. The general alignment of depositional features is determined by the direction of prevailing winds. In addition the form and size of depositional features largely depends on the supply of sand.

Ripples- *are the smallest features of sand deposits produced by small scale turbulence. They create an undulating desert terrain, making it difficult to move across deserts.*

Sand Dunes – Sand dunes are asymmetrical mounds with a gentle slope in the upwind direction and steep slope called a ***slip face*** on the downwind side. Dunes migrate by erosion of sand by wind (saltation) on the gentle upwind slope, and deposition and sliding on the slip face, and thus are cross-bedded deposits.

Sand dunes form when there is:

(i) a ready supply of sand,

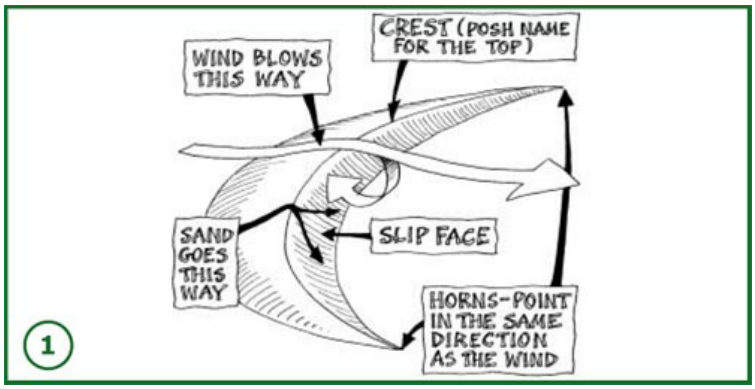
(ii) a steady wind, and

(iii) some kind of obstacle such as vegetation, rocks, or fences, to trap some of the sand

Sand dunes form when moving air slows down on the downwind side of an obstacle. The sand grains drop out and form a mound that becomes a dune. The types of sand dunes

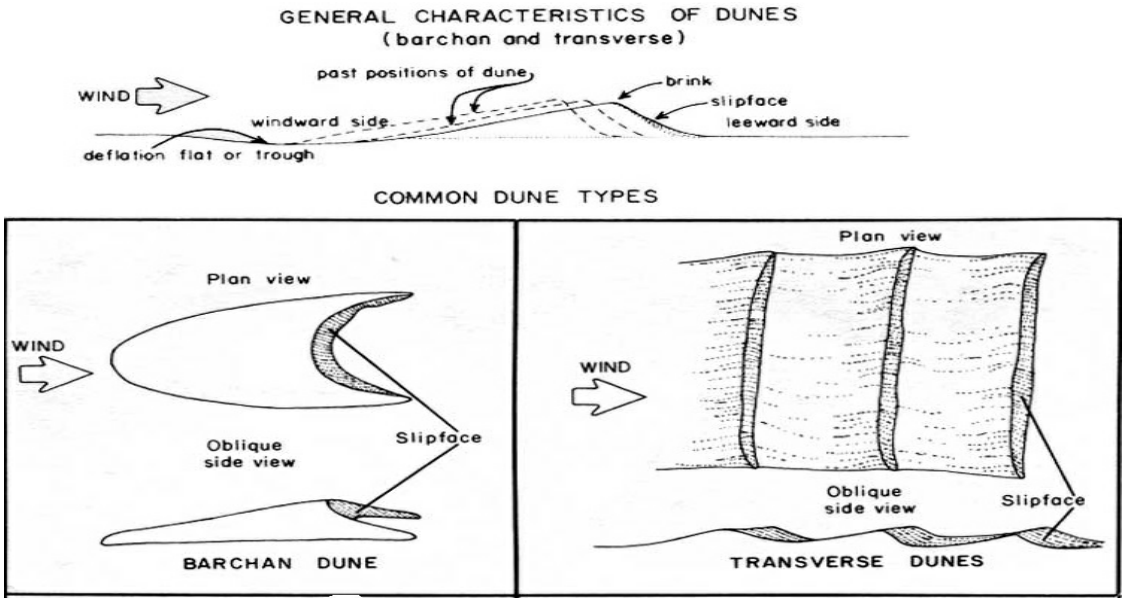
are:

Barchan Dunes - are crescent-shaped sand dunes which have two horns pointing in the downwind direction (to the direction of prevailing winds), and a curved slip face on the downwind side of the dune. They form in areas where there is a hard ground surface, less vegetation, a moderate supply of sand, and a constant wind direction. They have a gentle windward slope and a concave slip off face which advances downwind. Normally the formation of barchans is triggered by an obstacle such as a small bush or a rock which inhibit the movement of sand



These horns are caused by the migration of barchans where the rate of migration is greatest on the sides where the quantity of is greater than at the centre. Barchans may reach a height of 30m. Barchans are migratory and they follow the direction of prevailing winds.

Transverse dunes – are long ridges of deposited sand which are aligned to the prevailing wind which is unidirectional. They are also called large fields of dunes that resemble sand ripples on a large scale. They consist of ridges of sand with a steep face in the downwind side, and form in areas where there is abundant supply of sand and a constant wind direction.



Barchan dunes merge into transverse dunes if the supply of sand increases. Unlike in longitudinal dunes, the ridges of transverse dunes lie across the direction of prevailing winds.

Longitudinal or seif dunes– are elongated ridges lying parallel to the prevailing wind.They assume an extensive form reaching heights of 100m and 200m long. Seif dunes are

thought to develop from barchans when secondary cross winds merge a series of barchans. Where cross-winds blow frequently, the windward horn will receive more sand resulting in its merging with the nearby barchan dune. Once formed the seif dune is maintained by prevailing winds. Their migration, however, is not very pronounced as opposed to the case of barchans.

Parabolic dunes – are crescent shaped dunes which resemble barchans but different from barchans in that their horns point to the direction where wind is coming from. They have slip off faces on the direction where wind comes from and they are formed in areas where the supply of sand is limited and where the sheer force of wind is limited.

Star dunes – these are complex dunes whose shape resemble a star.

Loess deposits- Loess is thewind-blown sand and silt particles (loamy) found on desert margins. Loess deposits are formed when wind transportation carries fine sand and silt particles for longer distances even outside the desert. Once deposited on desert outskirts loess tends to develop into very rich agricultural soils. Under appropriate climatic conditions, it is some of the most agriculturally productive terrain in the world.

THE ACTION OF WATER IN DESERTS

Questions

(a) Describe and explain the nature of running water in present day deserts (9)
(b) Assess the significance of running water in the development of desert landforms. (16)

Sources of water for deserts

a) Infrequent or spasmodic rains which are usually heavy and short lived.

b) Exogenous rivers- these are rivers whose sources are outside the desert but pass through the desert areas e.g. the Nile River in Africa which cuts across the Sahara Desert; the Tigris River which cuts across Iraq; and the Euphrates River which cuts across Iran. The Niger River also cuts across the Sahara Desert, while the Colorado River passes through Arizona.

c) Oasis- or springs in deserts formed when the water table is exposed by wind deflation mentioned earlier.

d) Ephemeral or intermittent streams- these are streams that flow seasonally after storms in deserts.

Types or nature of running water in deserts (answer for question (a) above)

The main types/ nature of running water in deserts are sheet floods, stream floods (flash floods) and Exorgenic Rivers.

SHEET FLOODS

Sheet floods*- refers to the water that flows in unconcentrated form usually spread out on undisected uplands of deserts. Normally sheet floods flow in very thin layers of water. In*

deserts sheet floods occur on undisected uplands on the upper parts of the slopes. They also occur on rock pediments and top of alluvial fans.

Sheet floods are generated from the sudden infrequent downpours that occur in deserts. These downpours usually exceed infiltration capacity and they usually compact the ground, closing all the pore spaces in the process. This generates a lot of overlandflow in the form of sheet floods.

Sheet floods also occur on the mouths of wadis, when water from the wadis spread out on top of the alluvial fans as it flows towards the salt lakes called playas.

Impact of sheet floods

According to McGee (1937) sheet wash usually occur in thin layers of water after storms and therefore, they have less erosive power. As a result, they are incapable of forming erosive landforms.

Again McGee suggested that sheet floods have less transportation power and as such they lead to formation/development of deposition features such as alluvial fans on the mouths of wadis and canyons. This is because as the water spreads out the velocity is reduced thus allowing deposition to take place.

Geomorphological role of sheet floods

According to McGee sheet floods are responsible for the formation of smooth surfaces on rock pediments and also the formation of depositional features such as alluvial fans. He regarded sheet floods as formative agents of rock pediments and alluvial fans but other Geomorphologists argue that sheet floods flow on such surfaces because they already exist not that sheet floods formed them. These Geomorphologists argue that sheet floods are to insignificant to have produced such landforms.

STREAM FLOODS

Stream floods*- refers to that water that flows in concentrated form usually in dissected uplands of deserts. The stream floods normally flow in steep sided and flat floored valleys called wadis. They are generated by sudden storms which normally exceed infiltration capacity leading to the formation of overlandflow.*

Impact of stream flows

Geomorphologists argue that stream floods are usually of very high velocity since the water flows in concentrated forms and as a result they have very high erosive and transportation power.

Geomorphological role of stream floods

Johnson argued that stream floods are responsible for the down cutting and formation of steep sided valleys like wadis and canyons. However, some schools of thought have the idea that wadis and canyons are a result of a past fluvial processes rather than present day stream floods.

EXORGENIC RIVERS

Refers to water that flows in rivers whose sources are outside deserts. These river lose a lot of water as they pass through deserts towards the sea or oceans due to high evapotranspiration rates in desert areas caused by high temperatures.

WATER LANDFORMS IN DESERTS

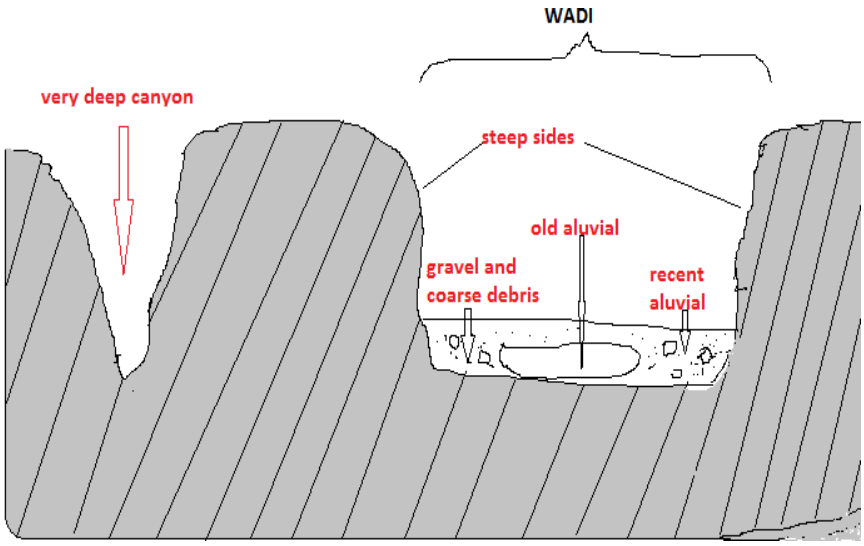
Question (b) assess the significance of present day running water in the development of present day desert landforms. [16]

- Wadis: steep sided and flat-floored valleys
- Canyons
- Rock pediments
- Oversized valleys
- Alluvial fans or bajada: features of deposition

Desert areas have distinct landforms that are different from other landforms found in other regions. One major problem of desert geomorphology is to decide how far these landforms are the products of the processes acting in deserts today.

It has been widely accepted that the legacy of the past is fundamental in explaining desert landforms. This is because the current levels of precipitation in deserts do not adequately account for water related features that are present in these areas. In fact rainfall in deserts is spasmodic, infrequent, unpredictable and insignificant to have sculptured these massive desert landforms. Geologists actually believe that present day desert landforms could have been formed during a past wetter fluvial era. It is also believed that desert areas could have at one time been receiving significant amounts of rainfall hence some features could have been formed during this period.

Wadis or arroyos- these are steep sided dry channels which have got flat floors that are gradually undergoing sedimentation.



These dry channels are water fashioned but some are very dry that the present scenario does not account for their formation, thus leaving the past wet climatic regime as the only possible explanation for the existence of wadis.

Oversized river valleys- these valleys are usually dry and even when they are wet, they can never be

filled with water because desert rainfall is too little. Their presence therefore support the idea that there was once a wetter period in deserts. The present day water action cannot adequately explain the existence of such large valleys. In fact most Geomorphologists argue that present day water action is only responsible for the modification of oversized valleys not their formation. Examples of such valleys include the *Tsondabi* and the *Tsonahabi*n Namibia.

Rock pediment- these are gently sloping rock surfaces found on the desert piedmont zone. Scholars such as McGee and Johnson attribute the formation of these pediments to stream floods and sheet floods in deserts. However some Geomorphologists argue that sheet floods and present day stream floods quickly diminish due to seepage into the alluvial fans and excessive evapotranspiration which means they have less erosive power to have formed rock pediment. These Geomorphologists believe that rock pediments could have been formed during a past wetter regimes. Present day running water is only modifying these rock pediments by depositing thin veneers of alluvial on the rock pediments.

Bajada and alluvial fans- these are massive depositional features formed on the mouth of wadis where stream floods empty their water onto near level plains. Because water exiting wadis will cover a wider space its velocity and erosive power is reduced hence deposition occurs to form alluvial fans. Alluvial fans can later merge to form a gigantic feature called a bajada that stretches to several hundreds of meters. The massive size of these features alone testify beyond doubt that they can't be attributed to present day running water.

Given the above evidence, it can be concluded that the formation of most water features in deserts dates back to a possible past wetter period or a past fluvial era when deserts were receiving more rainfall. The size of most of these features alone supports this assumption.

CLIMATE CHANGE IN DESERTS

Climate change is a process which involves a gradual change in the climatic conditions of an area, i.e. a decrease or increase in the amount of precipitation over a long period of time. In other words climate change is a process whereby the conditions of an area change from wet to dry or dry to wet over a long period.

Geomorphologists argue that desert areas experienced a change in climate from wet to dry conditions; and that the climate is still changing today. This means that deserts once experienced a wetter regime before the climate changed to present day arid conditions. According to Geomorphologists, this wetter period is responsible for the formation of most water related features seen in deserts today.

Evidence of climate change in deserts

This the evidence of the existence of a past fluvial era which was wetter than today's desert conditions. These evidences are grouped into:

- Geomorphological evidence
- Hydrological evidence

- Biological evidence [analysis of flora and fauna]
- Archeological evidence

1. Geomorphological evidence

(a) *Weathering*- some weathering products found in present day deserts point to a wetter period. For example in the western parts of Australian Desert where the area is underlined by sheets of laterites and chemically weathered crystalline rocks related to humid climates. The presence of these features suggest that deserts once experienced a wetter climate because in present day deserts, chemical weathering is minimum and/ or insignificant.

(b) The existence of *alluvial deposits comprising of chemically rotten residues* for example in the Australian desert also point to a wetter period. The granite terrain of the Arabian Desert are underlined by chemically rotten rock containing coal stone and finely weathered material which are typical characteristics of present day humid regions.

(c) The occurrence of *dust storms which contain red clay residues* in the Sahara Desert also testify the dominance of chemical weathering like oxidation and hydrolysis in the past when climate was wet.

(d) In the Arabian desert west of Riyadh, *limestone soil of that area have got solution pipes of more than 30m in depth forming tunnels and crevices which indicates that carbonation took place during a past wet period*. Present day desert climate with low rainfall and high evaporation rates due to high temperatures cannot account for the formation of these features.

2. Hydrological evidence

a) *Water fashioned features*- the existence of oversized valleys and deep steep sided wadis can only point to a wetter regime because present day rainfall amounts in deserts is too little to be responsible for their formation.

b) *Shrinking of water bodies*- lakes found in deserts were once very large and deep but now they are shallow and small for example the Mega Chad Lake in the Sahara which once covered an area of about 350 000km^2 but now covers less. This means that long back deserts received high amounts of rainfall. Another example is Lake Boreville in USA which has shrinked to a mere $1/10$ of its original size.

3. Archeological evidence

This involves the study of humans of the past which testify past wetter periods. They prove that the past climate was wetter.

a) *Rock painting*- rock painting found in the Arabian Desert show that people used to hunt big animals such as elephants, giraffes and buffalos. There are also rock paintings which show human occupation like fishing in lakes and cattle herding. These rock paintings prove that deserts were once wet because it is impossible for the big animals to survive in present day desert conditions.

b) There is also evidence of *small crocodile remains* found trapped the Tibetan Mountains. This means that crocodiles once survived in these areas long back during the wet periods.

c) *Flora and fauna remains*- using the carbon dating technique archeologists dated some of the animal and tree remains back to a wetter regime before climate change in deserts.

4. Biological evidence

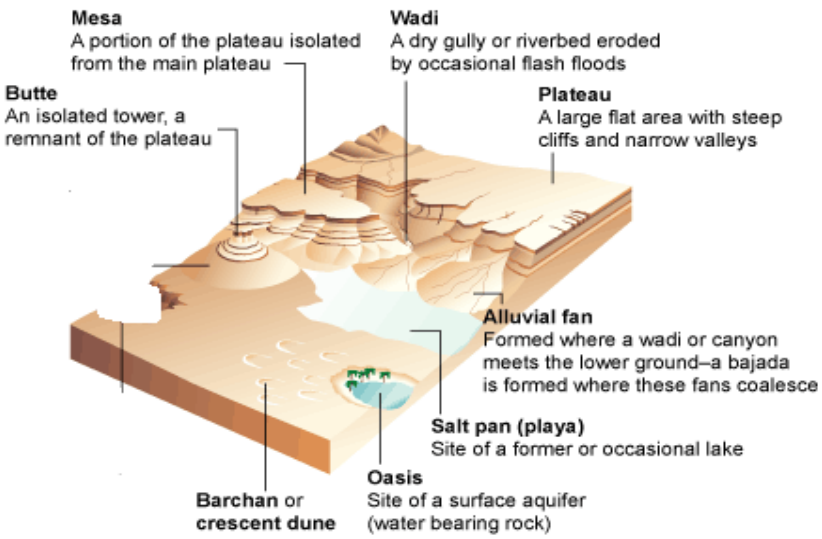
Analysts of other plant species has also shown that there were very *large forests* in deserts long ago. These forests disappeared because they cannot survive under harsh weather conditions of present day deserts.

EVIDENCE THAT SHOWS THAT DESERT CLIMATE IS NOW CHANGING

- Continuous increase in temperatures
- Occurrence of persistent droughts which are becoming more and more frequent
- Desertification process or the spread of deserts into non-desert areas
- Rainfall amounts which are becoming less and less.
- Extinction of certain animal and plant species and the changing of animal behavior due to climate change.

OTHER DESERT WATER FEATURES

When rain falls water does not sink down into the ground because the ground is too hard and there are no plants to trap it on the surface. The dry river bed called wadis can flood in minutes. This is called a flash flood.Although these floods may occur several years apart they produce a big influence on the desert landscape.They can produce features such as salt pan, alluvial fans, mesas and butte.

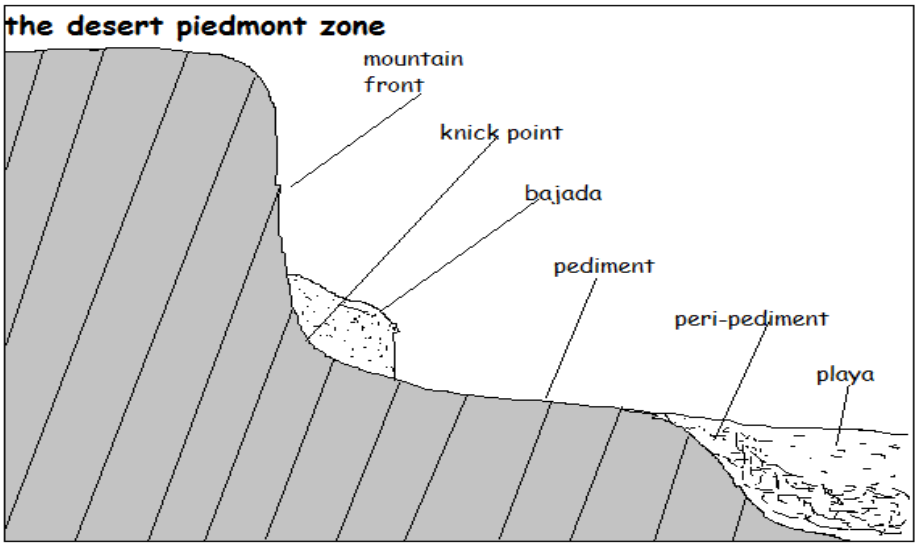

Mesa
A portion of the plateau isolated from the main plateau
Wadi
A dry gully or riverbed eroded by occasional flash floods
Butte
An isolated tower, a remnant of the plateau
Plateau
A large flat area with steep cliffs and narrow valleys
Alluvial fan
Formed where a wadi or canyon meets the lower ground–a bajada is formed where these fans coalesce
Salt pan (playa)
Site of a former or occasional lake
Oasis
Site of a surface aquifer (water bearing rock)
Barchan or crescent dune

A salt pan or Playa is a lake of salty water that dries out in the dry season to form a layer of salt crystals on the ground.Alluvial fans are deposited substances on the ground after being transported by a flood.Mesas and butte are hard rock landforms that have not been eroded away by the water.

THE DESERT PIEDMONT ZONE

Piedmont zone – refers to the rapid change in slope angle between the steep upper slope

and the gentler piedmont.



According to Small R.J. the desert piedmont zone refers to an area that separates desert uplands from the broad plains below or a transition from dissected uplands to the plains. The process of erosion is the chief cause for the formation of the piedmont zone.

Mountain front *- is the scarp or face of the mountain and is generally steep. The mountain front comprise mainly of a very steep slope ranging from 35 to 90^0. There is an abrupt change in gradient from mountain front to pediment zone. This surface (mountain front) consist of a bare rock where erosion, weathering and slope retreat occur. The formation of mountain front is thus attributed to back wearing process.*

Knick point or Piedmont angle – *this is an angle which separates the mountain front from the plain below. It shows an abrupt change of gradient from steep mountain front to a gentler pediment zone or a point of break from the mountain front to the rock pediment. Knick points are usually covered with alluvial fans derived from the weathered mountain front.*

Geomorphologists attribute the formation of nick points to lateral planation by running water. In other words stream floods are responsible for the formation of knick points.

Alluvial fan or bajada- refers to depositional features formed at the base of the mountain front. Streams deposit weathered debris (alluvial) at the mountain base as velocity declines due to a change in gradient. Bajada is formed due to the coalescence of alluvial fans deposited by ephemeral streams at the base of the mountain front. Bajada are evidence of effective transportation process on the upper part of the pediments.

Peri-pediment- *is made of deposited alluvial from the mountain front. The peri-pediment is wholly a result of deposition of alluvial on the lower part of the pediment. Its terrain is gentle and undulating. The peri-pediment marks the end of the pediment zone.*

Playas- *are ephemeral salt lakes which act as mouths of streams running from the mountain front. They have alluvial deposits and they quickly deplete because of high evaporation rates caused by high temperatures and strong winds. These salt lakes thus quickly dries up to become hard salt pans. However some playas can permanently hold water if the supply from surroundings is constant e.g. the Magkadighadi in Botswana.*

Pediment- is a gently sloping erosion surface or plain of low relief formed by running water at the base of a mountain. A pediment is typically covered by thin layers of

alluvium derived from upland areas.

Characteristics of Rock Pediments

- they comprise of a basal slope of low angle ranging from 7^0 to less than 1^0 on the lower part of the pediment
- they are concave in profile
- comprise of a bare solid rock surface which is sometimes covered by a thin veneer of alluvial
- they are smooth surfaced due to the effect of flash floods flowing on top of them

THEORIES OF PEDIMENT FORMATION

The formation of rock pediments remains a controversial issue. Although they are not exclusively desert features [for example they are also found in Savana region]; their formation remains a subject of debate among Geomorphologists. Several theories have been put in place in trying to account for the formation of rock pediments. These theories are divided into water and composite theories.

WATER THEORIES

McGee's sheet floods theory - according to McGee rock pediments in deserts are a result of lateral planation by sheet floods which caused the retreatment of uplands, scarps or mountain fronts. The infrequent or spasmodic (sporadic) storms in deserts generate large amounts of runoff in the form of sheet floods which are significant enough to downcut the mountain front thus causing its recession or backwearing. This creates an extensive rock pediment described above.

Evidence of sheet floods impact on the formation of pediments include

- ❖ the existence of smooth surface which McGee says was smoothened by sheet floods
- ❖ absence of material/debris or few materials (thin layer of alluvial) because of removal by sheet floods
- ❖ existence of knick point which McGee attributed to the process of downcutting by sheet floods
- ❖ gentle concave slope of the pediment which shows that erosion is no longer active

Criticisms of the theory

- ❖ Most rock pediments found in deserts are foliated (heavily jointed) in structure such that there is more seepage of water into the ground which will reappear downstream. This leaves no water or little amounts for flash flooding.
- ❖ It is well known that rainfall in deserts is very low so the combination of low rainfall and high evaporation means that the sheet floods quickly disappear and

become insignificant to account for the formation of pediments.

Johnson's stream floods theory (1937) - Johnson suggested that rock pediments are a result of lateral planation by stream floods rather than sheet floods. According to this theory, pediments are wholly a result of downcutting by streams, i.e. lateral planation by streams. Stream incision creates dissected uplands which are going to disappear by lateral planation leaving a pediment below.

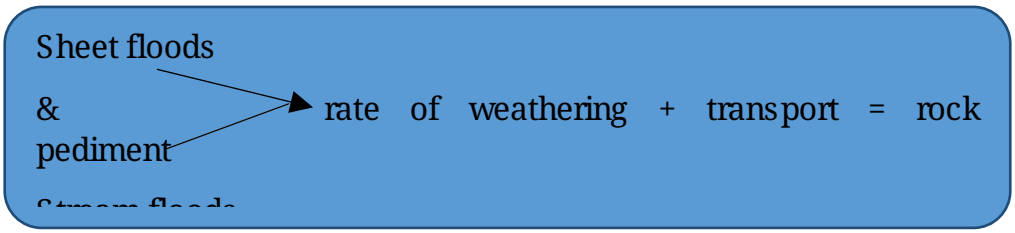
Evidence of stream floods

- ❖ existence of a sharp knick point angle
- ❖ infrequent, spasmodic storms can generate powerful streams such that infiltration capacity will be exceeded

Criticisms of the theory

- streams in deserts have very little erosional capabilities therefore they are insignificant to account for downcutting put forward by Johnson

Howard's stream and sheet floods theory - Howard acknowledges the importance of both stream and sheet floods in the formation of pediments. According to Howard, sheet and stream floods can be expressed as follows:



NB- the role either stream floods or sheet floods cannot adequately explain the formation of a rock pediment in deserts. There is therefore need to consider other geomorphological processes such as mass movements, weathering e.t.c.

Composite theory - The composite theory was started by Lawson and later used by Penk and King. According to these theorists, rock pediments in deserts are a result of scarp retreat or pediplanation/pedimentation processes. These processes are facilitated by weathering and mass movement on mountain front followed by active water erosion and transportation. In other words, the composite theories state that rock pediments in deserts are a result of scarp retreat. In fact the pediments are a remnant feature resulting from destruction of desert uplands due to geomorphological processes such as weathering, mass movement and erosion.

Lawson further states that the process of scarp retreat is initiated by faulting followed by the process of backwearing along the scarp. In addition Lawson pointed out that rock pediments are a transportation zone between the degrading zone on the mountain front and the alluvial zone.

Strengths

- the theory is very applicable in deserts of USA where Lawson made his observations and where mountain front have originated from faulting
- the theory is also applicable to geological structures that are in form of blocks
- the theory acknowledges that the pediments are a result of more than one process

Criticisms

- the theory is not applicable outside USA since America doesn't constitute the world's driest areas
- pediments are not confined to margins of inland as Lawson's theory suggest

DESERT GEOMORPHOLOGY

Question: describe and explain the main forms of weathering occurring in present day deserts.

There are various forms of weathering that occur in present day deserts. Both physical and chemical weathering operates in deserts. However the rate of chemical weathering is very slight owing to the absence of moisture.

Physical Weathering Processes

i) *Thermal shattering (exfoliation)* – is the most common type of weathering in hot deserts because of a large diurnal range of temperature caused by very high day temperatures and very low night temperatures. Day temperatures exceed 40^0C, while night temperatures are very cold. In addition, absence of vegetation cover means that rocks are exposed to the sun's heat. Consequently, exfoliation becomes a dominant weathering process in deserts leading to the development of curvilinear sheets joints as the outer rock layers expand faster (remember rocks are poor conductors of heat). Exfoliation is most active on crystalline rocks like granite. However, some Geomorphologists ague that exfoliation is minimum in deserts because the absence of moisture means that there is no sudden cooling of rocks.

ii) *Pressure release or dilatation (unloading)* -is also very active in deserts due to high rates of wind water erosion facilitated by lack of vegetation/protective cover. Aeolian and water erosion expose buried rocks leading their expansion. This expansion lead to the formation of curvilinear joints (pseudo bedding plane) on exposed crystalline rocks. This process expose the rock to other weathering processes like exfoliation.

iii) *Salt crystallisation*- occurs in deserts due to the abundance of salts and saline water. Spasmodic or erratic storms cause the salts to dissolve and accumulate inside rock's pore spaces, and when dehydration occurs during the day, salt

crystals remains inside the pores. As the process continues, the pore spaces become filled with salt crystals, causing mechanical stress and granular disintegration of rocks. Salt crystallisation is also aided by capillarity which is high due to high evapotranspiration rates.

iv) *Frost shattering*- occurs in deserts on mountain peaks that are sometimes covered by ice. As the water freezes inside the rock cracks at mountain tops, ice wedging takes place leading to block disintegration. NB frost shattering is only restricted to mountain peaks in deserts such as those found in Iran and Afghanistan.

v) *Root wedging*- also occurs in deserts when roots grow inside cracks causing expansion and disintegration of rocks. However, root wedging is minimum due to low vegetation cover in deserts.

Chemical Weathering Processes

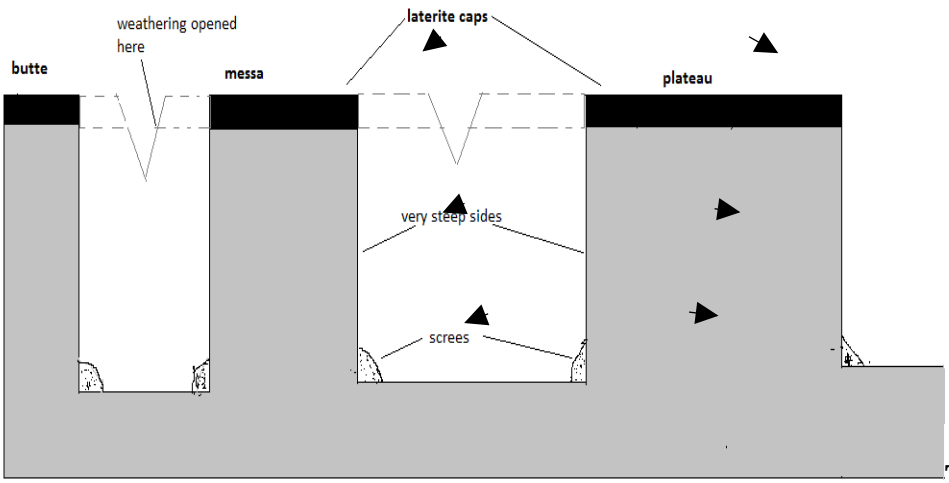
High temperatures facilitates chemical reactions. Moisture for chemical weathering is also available in the form of spasmodic storms. Examples of chemical weathering processes in deserts are carbonation in limestone rocks, oxidation in ironstone rocks, hydrolysis in crystalline rocks and solution in rocks that contain salts. However, chemical weathering remains very slight in deserts due to prevailing arid conditions (lack of moisture).

DESERT DISSECTED UPLANDS

Question: describe and explain the main features of dissected uplands in hot deserts.

The word dissection means deeply eroded or cut by moving water. The main features of dissected uplands include flat topped plateaus, messas, buttes, canyons, wadis and alluvial fans. These features are mainly a result of past fluvial process of erosion. Vertical incision followed by lateral erosion occurred on uplifted land leading to the formation of flat-floored and steep-sided valleys called wadis.

Butte, Messa and Plateaus



These are steep-sided, flat topped features found in deserts. They form the flat-topped landscape in hot deserts such as those found in the western Australian Desert. They usually have laterite caps

suggesting past fluvial formation. The butte is the smallest followed by messa then plateau.

The formation of these flat topped features is the same as the formation of duricrusts and laterites. The hard lateritic caps resist erosion that's why these features are flat-topped. Weathering and erosion break the laterite cap of the desert landscape into smaller units shown in the diagram.

DESERT ECOSYSTEM

Question: outline the characteristic features of arid and semi-arid ecosystems.

Definitions:

Ecosystem *– is a holistic concept which encompasses the interaction of the living and non-living components within a given environment. In other words it is a community of organisms co-existing together to form a recognisable self-contained community.*

NB- desert ecosystems echoes a blueprint of the climatic and environmental conditions found in these areas.

Environmental and Climatic conditions of Deserts

Precipitation/rainfall- deserts receive very low annual rainfall totals (not exceeding 300mm). Rainfall here is infrequent, unreliable and erratic and it is of very high intensity but short-lived.

Temperatures- day temperatures are extremely high; exceeding 40^0C sometimes. This encourage excess evapotranspiration rates. High ET leads to increased salinization and translocation of minerals upwardly in a process called capillary action. The diurnal range of temperature is also very high.

Winds- deserts are characterised by prevailing winds [winds blowing from the same direction always] of very high intensity; sometimes developing into dust storms that have very strong erosive and transportation capabilities. Generally, winds are hot and dry encouraging high ET rates.

Soils- desert soils are sandy, coarse, poorly developed, and shallow; a reflection of inadequate and incomplete weathering. The soils are also saline and unfertile due to lack of vegetation cover which is essential for humus accumulation. As a result desert soils are incapable of supporting crop production and the growth of vegetation cover.

Animals- there are some animals that live in deserts; but only few of these animals which have adapted to harsh conditions can survive there.

Vegetation- desert ecosystems have the least biomass compared to any other climate. Most plants found in deserts are xerophytes which have adapted to dry conditions and halophytes which have adapted to saline conditions.

Adaptation of plants and animals in deserts

An adaptation is a characteristic or trait developed by an organism to assist in its survival.

Adaptation *can be structural(e.g. plants have big leaves to maximize transpiration under humid conditions) or behavioural (e.g. the rabbit will squeak when it is being chased to warn other rabbits that there is danger).*

NB- the flora and fauna in deserts display a wide variety of structural, physiological and behavioural forms of adaptations to the current prevailing conditions.

Desert plants are drought tolerant plants which are mostly xerophytes. They have mechanisms meant to withstand dry conditions. These adaptations are given below:

- long tap roots to draw underground water
- xerophytes- e.g. cactus inorder to minimise transpiration by having spikes or thorns in places of leaves
- waxy covered leaves to reduce water loss
- desert plants reduce metabolism when it is dry by simply drying out but ready to resume growth when it is wet
- huge trunks and tubers to store water
- fleshy stems to store water
- sunken stomata to minimise transpiration
- produce seeds which lie dormant for a long time and germinate when little rains fall; these seeds are covered with hard crusts or shells to extend their lifespan
- short life cycle e.g. flowering plants and herbs to maximise chances of survival of future generations by providing humus through decomposition
- lateral extension of roots or spreading roots for quick absorption of water during infrequent short-lived, erratic storms

Adaptation of animals

- Nocturnal activity- to prevent excessive heat during the day e.g. through sweating and respiration. Animals also sleep during the day in shades and caves to prevent daytime heat.
- Animals also barrow into the ground e.g. reptiles, rodents and mice to avoid excessive heat of the daytime. Barrowing of the ground is also done by snakes for warmth during the cold season.
- Animals also pass out concentrated urine and dry faeces inorder to minimise water loss from their bodies. A good example is the J erboa.
- They also adapt to desert conditions by storing fat at the humps of their backs for use during the absence of food, e.g. camels. Camels also have the capacity to go for days without drinking water due to the absence of reliable sources of water.

- Animals also develop large broad hooves to be able to walk in desert sands.

THE CONCEPT OF SUSTAINABILITY IN ARID AND SEMI-ARID ENVIRONMENTS

Question: with reference to examples, discuss the concept of sustainability in arid and semi-arid environments.

The concept of sustainability refers to the wise use of desert resources by people inorder to satisfy their demands but without compromising the ability of future generations to meet their own demands. Deserts are utilised in a number of ways:

Mining- desert environments can be utilised through mining of minerals found there. For example in Botswana there is diamond while there is crude oil in Libya. Uranium is also mined in Namibia. Revenue generated from these mining activities is used to meet the needs of these countries.

Agriculture- arid areas have Exorgenic Rivers which can be used for irrigation practises. Dams and boreholes can also be put in deserts to practice irrigation farming and to increase to water holding capacity of deserts. A good example is Egypt where irrigation farming has been practiced along the Nile River since ancient times. In Iran irrigation farming in deserts is also practiced along the Jordan River. Such areas where irrigation farming is done have become greenbelts for arid and semi-arid environments. Pastoral farming is also done in arid and semi-arid regions e.g. in Botswana where large-scale cattle ranging is done; sometimes under zero-grazing. Both commercial and subsistence pastoral farming is done here.

Tourism- deserts are also utilised by a wide range of tourist activities to generate revenues. Most desert features such as wadis, canyons, and sand dunes attract tourists [are scenic attractions]. Because of this some countries like Botswana have become popular tourist destinations and they get a lot of income returns in the form of forex. In addition some countries like the United Arab Emirates have become tourist heavens because of desert attractions.

Sporting activities- desert areas have also become very famous venues for motorcar and bike racing. In the Sahara Desert for example, there is the most popular annual Dakar Paris race and this attracts thousands of tourists

Testing of weapons- because of their solitude, deserts have become best sites of testing dangerous Arsenals such as nuclear weapons. For example the Mojave Desert of America and other deserts in Iran and Iraq.

Dumping of hazardous materials- deserts have also become best sites for the dumping of hazardous substances. This is done because there fewer people in deserts and there is a smaller amount of flora and fauna which means chances of endangering life are very slim.

Problems associated with the sustainable utilization of arid and semi-arid environments

Question: Discuss the problems associated with the sustainable utilisation of arid and semi-arid environments. [16]

Mining of minerals cause land degradation in already fragile environment and this increase aridity. Worth-noting among these mining activities is open cast mining which cause deforestation through the removal of the overburden. This leaves bare unproductive soils which are vulnerable to soil erosion and land degradation.

Irrigation contribute to the problem of salinization which already is a huge problem associated with desert soils. This worsens the problem of salinity hampering the growth of vegetation in the process. This further reduces the amount of biomass in desert ecosystems. On the other hand pastoral farming lead to overgrazing of already fragile environments increasing the risk of soil erosion.

Tourism increase pollution of desert areas and also cause problems of cultural erosion. Tourists usually carry along with them plastic bottles and other non-biodegradable things which they dump in deserts after use during their tours. In addition activities such as car racing is likely to leave behind torn tyres leading to land pollution. Tourists are also likely to erode local traditions and cultures as locals try to imitate foreign cultures.

Tourists also engage in activities such as spot hunting which ultimately reduce the populations of desert animals. Some animal species which are targeted most are facing the risk of extinction due to such activities coupled with illegal hunting and unwarranted killing of dangerous animals like lions.

Testing of dangerous weapons and the dumping of hazardous wastes in deserts endangers desert ecosystems. In fact they reduce desert vegetation and threatens animal life directly by poisoning of animals and indirectly by polluting underground and ground water sources. The disturbance of life forms in an already fragile environment is said to be devastating.